MIDWEST TECHNICAL INPUT REPORT

Prepared for the US National Climate Assessment

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INTRODUCTION TO THE REPORT

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The technical input report for the Midwest region consists of twelve whitepapers along with background information for a potential focus box on Mississippi levees. The whitepapers were commissioned from experts within the Midwest region and address critical sectors, systems and processes. The intent of the whitepapers is to support the drafting of the Midwest chapter for the 2013 report of the US National Climate Assessment. The whitepapers are also intended to stand alone and will be posted on the website of the Great Lakes Integrated Sciences and Assessment (GLISA) center. The length, organization and formatting varies between the different whitepapers, reflecting the diversity, concerns and available literature for the different sectors. The whitepapers incorporate both peer-reviewed and gray literature.

A review of the whitepapers will commence 2 March 2012. All whitepapers will be reviewed by at least two experts. Authors will revise the whitepapers to incorporate relevant reviewer comments. Our intent is that the revised whitepapers will be available by approximately 15 April 2012. The whitepaper authors are also preparing a synthesis manuscript for submission to a referred journal.

Historical Climate and Climate Trends in the Midwestern USA
Jeff Andresen, Steve Hilberg, and Ken Kunkel

Introduction

The Midwestern USA, defined here as a region stretching from the Minnesota, Iowa, and Missouri eastward to Michigan and Ohio ranks among the most important agricultural production areas of the world and contains a significant portion of the Great Lakes Basin, the largest supply of fresh water in the world with more than 20% of the global total (Quinn, 1988). The region spans a region of steep climate, geological, and vegetation gradients. Geological features transition from ancient, crystalline rocks overlain by glacial sediments in the north to a series of sedimentary rock strata covered by deep unconsolidated deposits across central sections to igneous/volcanic rock deposits within the Ozark Plateau in southern Missouri (Vigil et al., 2000). Changes in elevation are relatively minor, ranging from less than 150m above sea level along the Ohio River Valley to more than 400m in the Superior Uplands of northern Minnesota, Wisconsin, and Minnesota and across sections of the Ozark Plateau in Missouri and the Appalachian Plateau in eastern Ohio. Native vegetation varies greatly across the region, ranging from boreal forest in far northern sections to grassland across central and western sections to hardwood forest in the south and east to savanna in between. This pattern is strongly related to soil type, which ranges from loess-dominated soils across most western and central sections of the region to alluvial soils near the major rivers to coarse-textured, highly heterogeneous soils in northeastern sections resulting from repeated glaciations to relatively old, highly-weathered soils in the southeast.

- Controls on Regional Climate

The current climate of the Midwest region is chiefly governed by latitude, continental location, large scale circulation patterns, and in northeastern sections by the presence of the Great Lakes. Day-to-day and week-to-week weather patterns are generally controlled by the position and configuration of the polar jet stream in the winter and transition seasons, with somewhat less influence in the summer, when the region is also influenced by frequent incursions of warm, humid air masses of tropical origin (Andresen and Winkler, 2009). The type and frequency of air masses moving through the westerlies is strongly dependent on the location of longwaves and the configuration of the jet stream across the Northern Hemisphere and the North American continent. Climate in the Midwest is a direct reflection of four primary airmass types from different source regions: 1) northwestern Canada (continental polar), 2) Gulf of Mexico/southern United States (maritime tropical), 3) Hudson Bay/northeastern Canada (continental polar), and 4) northern Rockies/Pacific Northwest (maritime polar) (Shadbolt et al. 2006). Less frequently, airflow originates from the East Coast and western Atlantic and on occasion from the southwestern United States and Northern Mexico. The relative importance of the different airflow source regions varies with season.

Migratory midlatitude extratropical cyclones are an important component of regional climate, responsible for a significant portion of annual precipitation (Heideman and Fritsch 1988). Cyclogenesis is driven by upper-atmospheric circulation and cyclone tracks are dictated by the amplification and propagation of Rossby waves in the mid-latitudes. There are several principal areas of cyclogenesis in North America. Of particular importance for the Midwest are the Alberta and Colorado cyclogenesis regions, both of which are located on the leeward (downwind) side of the Rocky Mountains (Whittaker and Horn 1981). The Midwest also experiences a number of cyclones that form along the western Gulf Coast, while approximately 20% of cyclones form within the region itself (Isard et al., 2000). Tropical cyclones, with origins in tropical and subtropical oceans, occasionally move into the region during the late summer and fall months following landfall in the southern or eastern USA and may bring widespread rainfall. Fortunately, wind or other related damage from these storms in the region is rare.

There are some existing statistical links between upper tropospheric flow and seasonal weather patterns across the region with global atmospheric teleconnection indices, but in general they are not as strong as in other regions of the USA (Hansen et al., 2001). For the El Niño/Southern Oscillation (ENSO), there is a tendency for an enhanced subtropical jet stream during negative phase (El Niño) winters across the southern United States, while the main polar branch of the jet stream retreats to a more northward than normal position across central Canada. As a result, the Midwest tends to experience weaker winds aloft, fewer storms and milder than average temperatures (Halpert and Ropelewski, 1992). During positive phase (La Niña) events, jet stream flow tends to be relatively meridional across North America, with either much above or below normal temperatures and wetter than normal weather across southeastern sections of the Midwest. Statistical links with ENSO in other seasons (especially the transitional fall and spring seasons) are relatively weak or non-existent, although a tendency for wetter and cooler (drier and warmer) than normal weather has been observed over at least portions of the region during the summer months during negative (positive) phase events (Carlson et al., 1996).
There are also established links with Midwestern weather patterns and the North Atlantic Oscillation (NAO). A positive NAO phase represents a deeper than normal low pressure system over Iceland and a stronger high pressure system near the Azores, whereas these systems are weaker than normal during a negative NAO phase (Rogers, 1984). Portions of the Midwest, especially eastern sections, tend to have above average temperatures (Halpert and Ropelewski, 1992) and above normal precipitation totals during winter and spring seasons with positive NAO phase, although the link is not particularly strong (Rodionov, 1994; Hurrell, 1995). A link to temperature and precipitation in the USA to the Pacific North America pattern (PNA) has been demonstrated, mostly in the winter and nearby months Leathers et al. (1991). In the Midwest, both variables are generally negatively correlated with the PNA., A negative correlation between the phase of PNA and precipitation totals was found in a study of wintertime precipitation Rodionov (1994). During the positive phase of PNA (with upper air ridging across western North America and troughing across the east), cyclonic activity across the region tends to be of northern origin and contains relatively less precipitation. During the negative phase, there is a greater frequency of cyclones originating in the southern plains which tend to contain more Gulf of Mexico-origin moisture, resulting in greater precipitation totals across the Midwest (Isard et al., 2000).

Finally, it is also important to consider the influence of smaller scale systems on the region's climate. Mesoscale convective weather systems in the form of clusters of showers and thunderstorms account for approximately 30% to 70% of the warm-season (April-September) precipitation over the Midwest region, with an even greater percentage during the

June through August period (Fritsch et al., 1986). More recent studies have further identified links between precipitation spatial patterns and major land use boundaries in the region, with enhanced warm season convection along and near boundaries between agriculture- and forest-covered landscapes (e.g. Carleton et al, 2008).

- Influences of the Great Lakes

The proximity of the Great Lakes has a profound influence on the weather and climate of northeastern sections of the region. Overall, so-called 'lake effect' influences result in a cloudier, wetter, and more moderate climate in areas downwind of the lakes (e.g. Michigan, Ohio) than in areas upwind or away from the lakes. These influences are related to three major physical changes associated with air flowing across the surface of the lakes and onto nearby land surfaces: changes in friction/surface drag, changes in heat content, and changes in moisture content (Changnon and Jones, 1972). It is important to note that these modifications typically act in combination.

Arguably, the spatially most widespread lake effect-associated impact is a change in the amount and frequency of cloudiness, which in turn directly impacts insolation rates and air temperatures. In areas directly downwind of the lakes, given climatological source regions of relatively cold continental polar or arctic polar air masses in the interior sections of northern North America and the Arctic, a majority of lake-related cloudiness is associated with northwesterly wind flow across the region during the fall and winter seasons. Enhanced cloudiness results in mean daily insolation rates in that are less than 75% of rates in areas upwind of the lakes at the same latitude, ranking the region statistically among the cloudiest areas of the country (Andresen and Winkler, 2009). During the late spring and summer seasons when lake water temperatures are relatively cooler than air and adjacent land surfaces, the impact on cloudiness is symmetrically opposite, as the cooler water leads to relatively greater atmospheric stability, general low-level sinking motion, and to fewer clouds over and immediately downwind of the lakes.

Other modifications include moderated air temperatures, with a general reduction in temperatures in downwind areas during the spring and summer seasons and an increase during the fall and winter seasons. Combined with the enhanced cloudiness, daily and annual temperature ranges are also reduced. Changnon and Jones (1972) estimated that mean winter maximum and minimum temperatures in areas just east of the lakes are 6% and 15%, respectively warmer than locations upwind of the lakes, while mean summer maximum and minimum temperatures on the downwind side are 3% and 2% lower than those upwind, respectively. Climatological extreme minimum temperatures in areas within 20km of the shores of the Great Lakes are as much as 20ºF warmer than those at inland locations at the same latitude across the state. The impact is somewhat less in the summer season, with extreme maximum temperatures in coastal areas are as much as 14ºF cooler than those at inland locations across the state (Eichenlaub et al. 1990).

Given enough atmospheric lift and moisture, lake effect clouds may also produce precipitation. Altered precipitation patterns are among the most significant lake influences on regional climate. So-called lake effect snowfall greatly enhances the seasonal snowfall totals of areas generally within 100km of the downwind shores of the lakes (Norton and Bolsenga 1993). For example, Braham and Dungey (1995) estimated that 25-50% of the yearly snowfall totals on the eastern shores of Lake Michigan could be attributed to lake effect snowfall.

Current Regional Climate

- General Description

As noted earlier, Midwestern climate conditions are largely determined by the region's location in the center of the North American continent. The generic Modified Koeppen classifications for the region range from Mesothermal, humid subtropical (Cwa) across far southern sections of the region to Microthermal humid continental hot summer (Dfa) across central sections to Microthermal humid continental mild summer (Dfb) across northern sections. Average annual temperature varies by about 20°F across the region (Figure 1) from less than 38°F in northern Minnesota to more than 60°F in the Missouri Bootheel. Seasonally, the greatest range in temperature across the region occurs during winter (December-February) with the least during the summer months (June- August). Seasonally, mean temperatures across the region typically peak in late July or early August and reach minima during late January or early February. Coldest overall temperatures tend to be observed in northern interior sections away from the lakes. Base 50°F seasonal growing degree day totals, a temperature-derived index of time spent above the 50 degree threshold, range from around 2000 in far northern Michigan and northeastern Minnesota to over 4000 in southern Missouri and Illinois.

Average annual precipitation increases from northwest to southeast across the region (Figure 2) ranging from about 20 inches in northwest Minnesota to 47 inches in southern Missouri and along the Ohio River. Precipitation occurs in all months and seasons, but is generally greatest during the warm season and least during the winter months. The degree of seasonality increases from east to west across the region. Average summer rainfall exceeds12 inches across most western sections, accounting for almost 50% of the annual total. Snowfall in the Midwest region is generally associated with either large, synoptic-scale weather disturbances or with the lake effect phenomenon, which may lead to highly varying snowfall totals over only short distances. Average annual snowfall varies from less than 10 inches in the far south to more than 200 inches in Michigan's Upper Peninsula, where seasonal snowfall totals and seasonal duration of snow cover are climatologically among the greatest of any location in the USA east of the Rocky Mountains.

Vulnerabilities

Weather and climate have major influences on human and natural systems in the Midwest, although the overall impacts are relatively less than in other sections of the U.S (Cutter and Finch, 2008). Agriculture is a major component of the Midwestern economy, with over $200B in farm gate value (USDA/NASS, 2008). The region has over 400,000 farms and is responsible for a significant portion of total global corn and soybean production. The Midwest is also a major producer of fruits, vegetables, dairy and beef cattle, and pigs. Agricultural production in the Midwest is critically dependent on weather. Frequency and amount of rainfall, heat stress, pests, ozone levels, and extreme events such as heavy precipitation, flooding, drought, late spring or early fall freezes, and severe thunderstorms (high winds, hail) can seriously affect production.

The risks of significant losses from such events are often higher for smaller producers and for specialty crops.

The major urban centers in the region, which include Chicago, Cincinnati, Cleveland, Detroit, Indianapolis, Milwaukee, Minneapolis-St. Paul, and St. Louis, are more sensitive to some weather and climate events due to the specific characteristics of the urban environment such as building density, land use, urban sprawl, and proximity to the Great Lakes. Extreme temperatures and dewpoints can have large impacts on human health, particularly in the urban core where the urban heat island effect elevates summer afternoon temperatures and prevents cooling at night. Severe storms, both winter and summer, result in major disruptions to surface and air transportation that often have impacts well beyond the region. During the winter, cities such as Chicago, Milwaukee, and Cleveland are susceptible to lake-enhanced snowfall during winter storms. Extreme rainfall causes a host of problems, including storm sewer overflow, flooding of homes and roadways, and contamination of municipal water supplies. Climate extremes combined with the urban pollution sources can create air quality conditions that are detrimental to human health.

The region serves as the nation's center for air and surface transportation; weather and climate extremes influence each form—commercial airlines, barges, trains, and trucks. Severe weather, including floods and winter storms, either stops or slows various forms of transportation for days and sometimes weeks. The Mississippi River, Ohio River, and the Great Lakes are used intensively for barge and ship transport; high and low water levels and ice cover, all determined largely by climate conditions, affect barge and ship traffic.

Human health and safety are affected by climate conditions. Temperature extremes and storms have impacts on human health and safety, including loss of lives. Tornadoes, lightning, winter storms, and floods combined annually lead to many fatalities. Over the recent 15 year interval (1996-2010), approximately 104 weather-related deaths occurred per year across the 8 Midwestern states while approximately 823 injuries occurred (www.weather.gov/om/hazstats.shtml). The occurrence of vector-borne diseases is modulated by climate conditions.

With several large urban areas, as well as miles of shorelines along the Great Lakes and other lakes, tourism is a large business sector in the Midwest. Climate conditions can greatly affect the number of tourists that decide to travel to and within the Midwest. Temperature extremes and precipitation fluctuations in the summer affect winery production, lake levels for fishing and other water activities, golf course maintenance, and state park visits, as well as attendance at sporting events and historical sites. In the winter, recreational activities such as skiing and snowmobiling are very dependent on the large annual fluctuations of snowfall and temperature across the region.

Specific major climate vulnerabilities include:

- Regional Floods

Flooding is an important and costly issue along Midwestern rivers (NRC, 2006). The Mississippi (1927, 1965, 1993) and the Ohio (1913, 1937, 1997) Rivers have experienced some of the most costly flooding events in U.S. history. The largest of these, the 1993 Mississippi River flood, was the 2nd costliest flood in modern times (after Hurricane Katrina), with most of these losses occurring in the Midwest (Parrett et al., 1993). In a study across the central states of the U.S., Changnon et al. (2001) ranked Iowa first, Missouri fourth, and Illinois sixth in state losses due to flooding during the 1955-1997 period. In addition to agricultural losses and direct damage to homes and infrastructure, floods can cause national disruptions to transportation because of the region's role as the center of the surface and riverine systems. In the 1993 flood, bridges, railroads, and the river were all shut down for periods of weeks to months. A more recent flood event in eastern Iowa in 2008 led to massive flooding in Cedar Rapids, IA when the levels on the Cedar River exceeded the previous record by more than 11 feet and led to total damages on the order of $10B (Temimi et al, 2011). In response, the city created an award-winning redevelopment plan that will help mitigate against the impacts of floods in the future (http://www.cedar-rapids.org/city-news/flood-recovery-progress/floodrecoveryplans/pages/default.aspx).

Flooding along the Ohio River Valley during the winter season has been linked to upper tropospheric teleconnection patterns. La Nina (cool or negative phase) conditions in the Pacific have been shown to be significantly associated with wetter winter conditions and El Nino (warm or positive phase) with drier winters (Coleman and Rogers 2003). The Pacific-North American (PNA) teleconnection index is even more strongly linked to the Ohio River Valley winter moisture with zonal(meridional) flow being related to wet(dry) conditions. PNA mode was strongly zonal during the period leading up to the 1997 Ohio River flood as well as during the 1937 flooding event.

While many flooding events are due to persistent patterns in heavy rainfall like the ones above, another type of flooding occurs in the spring due to melting snowpacks. In the spring of 1997, record floods occurred along the Red River of the North and the Mississippi River in Minnesota and Iowa due to snowfall totals exceeding average by 150 to 250 percent (Kunkel 2003).

- Severe thunderstorms

Severe thunderstorms can be accompanied by tornadoes, hail, lightning, and strong straight-line winds, causing property and crop damage and human injuries and death. Non-tornadic thunderstorms are the most frequently-occurring weather catastrophe (as defined by the insurance industry) type based on insurance losses in this region (Changnon 2010). The mean annual numbers of severe thunderstorms generally decrease from southwest to northeast across the region, with southwestern portions included in the nation's 'Tornado Alley' region of greatest severe weather frequency. Four states in the Midwest region, MO, IL, IA, and IN, ranked among the top 10 states with greatest frequency of hail catastrophes ($1M or greater damage) during the period 1949-2006, with relative rankings of 5th, 7th, 8th, and 9th, respectively (Changnon, 2008). Severe thunderstorm frequency varies by season across the region, with greatest frequency during late spring and early summer over southern sections and during mid-summer months across the far north. Most violent severe weather tends to occur during the spring.

- Summer drought, heat, and excess rain

Since most agriculture in this region is rainfed, the Midwest is highly vulnerable to summer drought. Major droughts can cause billions of dollars in losses. As the nation's and globe's "breadbasket", droughts can have substantial economic ramifications both nationally and internationally. Large scale regional droughts were relatively common in the Midwest during the period of 1895 to 1965, but since 1965, only the summer drought of 1988 has had severe impacts across the entire region. Due to the potentially large areas impacted, regional droughts may contribute to a large increases in world-wide commodity and food prices.

During the summer, convective events can produce excessive rain over localized areas. These events can produce flooding along small rivers and streams as well as in urban areas where drainage is not adequate. Despite typically being short-lived, these flash flooding events can leave behind much damage. Climatologically, the fraction of annual precipitation associated with the 10 largest events of the year increases from less than 0.3 across eastern Ohio to more than 0.5 across western sections of Minnesota, Iowa, and Missouri (Pryor et al., 2009a).

- Heat waves

Major widespread heat waves occurred in the region during 1934, 1936, 1954, 1980, 1995, 1999, and 2011 (Westcott, 2011), The 1995 heat wave, which lasted only 4 days, resulted in over 700 fatalities in Chicago, the most deadly U.S. heat wave in decades. Maximum daily temperatures were equal to or greater than 90°F for seven consecutive days, and greater than 100°F for two days at the peak of the heat wave. Even more importantly, there was no relief at night, as nighttime minimum temperatures remained above 80°F during the hottest days. Heat waves also cause major power outages and disrupt a number of economic activities. Climatologically, the number of days with temperatures reaching 90°F or greater in the 9 largest urban areas of the region (Chicago, Cincinnati, Cleveland, Detroit, Des Moines, Indianapolis, Milwaukee, Minneapolis-St. Paul, and St. Louis) average from 7 (Milwaukee) up to 36 (St. Louis) days each year, while the number of days over 100°F range from one every two years up to an average of two per year. The factors that determine the region's climate favor occasional episodes of intense heat that are frequently accompanied by very high humidity. The heat index combines temperature and humidity to estimate how hot humans feel. Currently, southern Midwest states experience between 6 (Indiana and Iowa) and 18 (Missouri) days per year with a heat index over 95°F while northern states and states that border the Great Lakes such as Michigan and Ohio experience less than 3 days per year. Bentley and Stallins (2008) identified three predominant synoptic features associated with extreme dew point (and heat wave) events across the Midwest: 1) The development and propagation of low pressure from the high plains through the upper Great Lakes with the surface advection of low-level moisture from eastern Nebraska, Iowa, Missouri eastward into Illinois and Indiana. 2) Healthy agricultural crops and sufficient soil moisture content throughout the region and 3) Restricted low-level mixing in the boundary layer allowing near-surface moisture to become trapped. The episodic nature of these events contributes to vulnerability because the population does not become acclimated to the intense conditions as is the case in warmer regions of the country (Anderson and Bell, 2011). There is evidence that adoption of simple community adaptive responses can mitigate the impacts of heat waves (Palecki et al., 2001) and that the adverse impacts of heatwaves across the region have declined in recent decades due to improved health care, increased access to air conditioning, and infrastructural adaptations (Davis et al., 2002). In response to the 1995 heat wave, the City of Chicago put together an extreme weather operations plan that included mitigation steps for the city to take during heat waves. These were implemented during a 1999 heat wave that was nearly as hot as the 1995 event, but fatalities were far less numerous. The city has also put together an ambitious Climate Action Plan that outlines both adaptation and mitigation strategies. One strategy is an aggressive "green roof" campaign, which has resulted in the installation of seven million square feet of green roofing. Green roof tops have been shown to reduce temperatures in urban areas by as much as 5.5°F, but concerns exist that they also increase surface dewpoint temperatures, which lead to smaller decreases in the apparent temperature (Smith and Roebber 2011).

- Winter storms

Major blizzards, snow storms, and ice storms create many problems for surface and air transportation. These in turn create numerous other impacts on the full spectrum of economic activities. Winter storms are the second-most frequent weather-related catastrophe in the region. The average annual incidence of snowstorms of 6" or greater snowfall in a 1-2 day period across the Midwest range from less than 0.5/year along the Ohio River to 1.0/year across most central sections of the region to 1.5 or more in northwestern Minnesota to more than 6/year along the lee sides of Lakes Superior and Michigan (Changnon et al., 2006). Major snowstorms are numerically most common in December in the lake effect snowbelt regions and during January elsewhere across the region.

Regional Climate Trends

- Paleoclimate

Ideally, the search for climatological patterns and trends thus requires consistent, unbiased data from as many long term sources as possible, as the magnitude of such trends may be far less than changes experienced on an annual, daily, or even hourly basis. In general, the amount and quality of data available for climatological analysis in the Midwest region decreases quickly with time into the past. Routine instrumental observations began in during the middle 19th century across much of the region, but the number and quality of those data and as well as differences in technology with current observations before the latter half of the 19th century complicate their use in such analyses.

There are a number of paleoclimatic records in the region based on fossil, sediment cores, tree rings, and other such evidence which illustrate large shifts in climate over geologic time scales, ranging from humid tropical conditions during the Carboniferous and Devonian eras 400-300 million Years Before Present (YPB) to frigid, glacial conditions as recently as 12,000 YBP during the end of the Pleistocene era. These major shifts are thought to be the result many factors, including tectonic drift of the continents, changes in the composition of the earth's atmosphere, periodic changes in the earth's tilt and orbit around the sun (Milankovitch cycles), and catastrophic singular events such as the impact of large meteorites and major volcanic eruptions.

More substantial paleoclimatological evidence of regional changes in climate is available since the end of the last major glacial epoch about 12,000 years before present. During early portions of the Holocene era approximately 10,000 years before present (YBP), climate in the region warmed rapidly following the end of the last major glacial epoch, resulting in a relatively mild and dry climate (versus current and recent past conditions) which lasted until about 5,000 YBP. During this period, the levels of the Great Lakes fell until the lakes became terminal or confined about 7,900 YBP (Croley and Lewis, 2006) and vegetation in the region gradually transitioned from a dominance of boreal to xeric species (Webb et al. al., 1993). Beginning about 5,000 YBP, climate cooled and precipitation totals increased, possibly associated with a change in jet stream patterns across North America from mostly west - east or zonal to more north - south or meridional (Wright, 1992). The cooler, wetter climate favored the establishment of more mesic vegetation, which is among the primary vegetation types today. Given a more meridional jet stream flow (and an increase in frequency of polar and arctic-origin airmasses into the region), there is also evidence to suggest that the frequency and amount of lake effect precipitation increased relative to previous periods at about 3,000 YBP (Delcourt et al., 2002). Finally, during the late Holocene, the region experienced a period of relatively mild temperatures from approximately 800A.D. to 1300 A.D. (sometimes referred to as the 'Medieval Warm Period') followed by a period of relatively cool temperatures from about 1400A.D. until the late 19^{th} Century (the 'Little Ice Age').

The mid-continent of North America was likely drier than present during the mid-Holocene, based on inferences from fossil-pollen data and estimates of past lake levels, and such conditions have often been explained by increases in the dominance (frequency and/or duration) of Pacific airmasses, zonal flow patterns, or enhanced westerlies (Schinker et al., 2006). The authors of this study also suggested that large-scale circulation patterns alone may not provide a full explanation of surface-moisture anomalies due to the dynamic interplay between surface conditions and atmospheric processes and that moisture availability (determined by atmospheric moisture flux and soil-moisture recycling) must also be considered.

- Instrumental Record

Temperature

Although there is tremendous inter-annual variability in regional temperatures, and there are multiplepoints in time when temperature shifts occurred, mean temperatures have increased overall since 1900 (Figure 3). Based on data obtained from the CRUTEM3 data set (Brohan et al., 2006), a homogenized data set with spatial resolution of 5 × 5°, annual mean temperature over the Midwest increased by approximately 0.059°C per decade during 1900-2010 period, increased 0.12°C per decade for the period 1950-2010, and 0.26°C per decade for the period 1979-2010. The trends and temporal patterns are somewhat similar to overall global trends which include an increase in mean temperature of about 0.8ºC since 1850 (IPCC, 2007).

Precipitation

Overall across the region annual precipitation across the Midwest generally decreased from the late 1800's through the dust bowl years of the mid 1930's, followed by a general increasing trend beginning during the late 1930s that continues to the present (Groisman and Easterling, 1994; Andresen, 2012), with an overall increase in precipitation during the past century. In general, annual precipitation has increased since 1895 by 2.5 – 5.5 inches, or a range of 5-15%. The 1930's were the driest decade on record regionally, while the recent 2-3 decades were the wettest (Lorenz at al., 2009). The increase in precipitation in since the 1930's has occurred both as a result of an increase in the number of heavy precipitation events (Kunkel et al., 2003) as well as overall increases in the number of wet days and multiple wet day events. In northeastern sections of the region, for example, the number of both single and 2-day consecutive wet day frequencies has increased more than 30% between the 1930s and the present (Andresen, 2012; Grover and Sousounis, 2002). Results from climate model experiments suggest that wetland drainage across some areas of the region over time has resulted in significant changes in the regional energy (sensible and latent heat flux) and radiation (long-wave radiation) budgets, possibly resulting in a warmer climate and a decrease in convective precipitation during the summer months (Kumar et al., 2010)

Seasonality of Temperature, Precipitation Changes

The increases in temperature and precipitation during the past century have not been consistent across season or time of day. Trend statistics for precipitation and mean temperature by state and season are given in Tables 1a and 1b for the periods 1895-2010 and 1981-2010, respectively. While changes in precipitation and mean temperature have been generally consistent during both time frames across states within the region, a relatively greater proportion of the regional warming occurred during the winter and spring seasons during the 1895-2010 period, and during the summer and fall seasons during the last 3 decades. In some sections of the region (e.g. IL, IN, MI) mean summer temperatures actually decreased with time, possibly due to landscape cover type changes associated with intensified agriculture over time (Pan et al., 2004). Just as importantly, much of the warming in recent decades has been associated with warmer nighttime (i.e. minimum) temperatures (Lorenz et al., 2009a). The latter results are consistent with the results of Zhang et al. (2001), who found largest increases in temperature across southern Canada between 1900 and 1998 had occurred in winter and early spring.

Seasonal differences were also noted for regional precipitation trends. The majority of the increase in precipitation since the 1930's has occurred during spring, summer, and fall seasons, accounting for over 90% of the increase in the overall annual precipitation. In contrast, during the most recent three decades trends for fall precipitation were negative for all states except OH, while trends for almost all other seasons and states were positive. There were also relatively larger increases in winter precipitation (0.039 inches/year on average).

Growing Season

The growing season length has increased across the region during the past several decades. In an earlier study, Skaggs and Baker (1986) concluded that frost free growing season length had increased an average of 14 days between 1899 and 1992. Similarly, Robeson (2002) found the length of the growing season in Illinois to have increased by nearly one week 1906-1997, much of the change the result of earlier last spring freezes. The date of the first fall freeze in the study was virtually unchanged during the study period. These regional trends are consistent with larger, hemispheric trends (Linderholm, 2006) and have been confirmed with satellite data depicting phenological changes over large areas Zhou et al. (2001). Averaged across the 8-state region over time (Figure 4), the frost free growing season length averaged about 155-160 days prior to the 1930s, then increased to around 160 days during the 1930s into the 1980s. Since the 1980s, it has continued to increase and now averages about a week longer than during the 1930s to 1980s period. In some contrast to the findings of Robeson (2002), the increase in length across the region is the result of both earlier last spring freeze and later first fall freeze.

Ice Cover

Among the impacts resulting from the recent warmer winter temperatures is a reduction in the amount and duration of ice cover on lakes across the Midwest region including the Great Lakes. This trend is well documented in previous studies by Magnuson et al. (2000) and Magnuson et al. (2010) which suggest an increasingly later onset of first ice cover on inland lakes in the region by 6-11 days since the middle 19th century and an increasingly earlier breakup of ice in the spring from 2-13 days during the same period. While available for a much shorter period of record, satellite imagery provides a more comprehensive estimate of ice cover changes on the Great Lakes as shown in Figure 5 for the period 1973-2009 (Wang et al., 2010). Average ice cover area across the Great Lakes during this period peaked during the late 1970's before decreasing by more than one half during the 1-2 decades of record. These numbers are in good agreement with the results of Duguay et al. (2006), who documented similar decreases in ice cover duration as well as trends towards earlier lake ice break up in the spring season during the period 1951-2000 in nearby areas in Canada.

Snowfall

Trends in seasonal snowfall across the Midwest during recent decades have varied by location. Average seasonal snowfall totals plotted for the thirty-year periods 1961-1990 and 1981-2010 in Figure 6 reveal some interesting patterns. In general, mean seasonal snowfall decreased across far southern sections of the region between the two periods, remained about the same across central sections, and increased across the north, especially in areas downwind of the Great Lakes. These trends are consistent with a reduction in the number of synoptic snowfalls and an increase in the frequency of lake effect snowfalls, possibly both linked with milder wintertime temperatures and the warmer, more open waters of the Great Lakes during the past few decades (Burnett et al., 2003). Similarly, temporal trends in the frequency of major snowstorms varied widely across the region during 1901–2000, with downward trends across southern sections and upward trends across the north (Changnon et al., 2006). In terms of snow cover, Dyer and Mote (2006) found minimal changes in North American snow depth through January, with regions of decreasing snow depths beginning in late January and continuing through March and into April, implying an earlier onset of spring melt. As noted by Andresen (2012) in sections of the Great Lakes region, there are distinct connections with snow cover and trends towards milder temperatures, with recent observations suggesting that milder winter temperatures are melting snow more quickly than in past decades even though more snow is falling.

Cloudiness

Given trends toward more annual precipitation and days with precipitation in recent decades, it is also logical to assume that cloudiness in the region has increased as well. Unfortunately, quality cloudiness and solar radiation observational records in the region are scarce. In an examination of observations obtained from U.S. military installations between 1976 and 2004, Dai et al. (2006) concluded that total cloud cover over most of the contiguous United States has increased during the period continued to 2004, including changes at Midwestern locations in the range of 1-3% per decade. While these findings are limited by the relative lack of data available for the study, they are consistet with the observed reduction in U.S. surface solar radiation from 1961 to 1990 reported by Liepert (2002) and average global decreases of 2.7% per decade noted by Stanhill and Cohen (2001). Besides the increasing frequency of precipitation, Minnis et al., (2004) attributed at least part of the recent increase in cloudiness to increases in high level cirriform cloudiness across the Midwest associated with jet aircraft contrails.

Humidity

The search for trends of humidity is complicated by the relative lack of quality observations and past changes in sensor technology. Most existing studies suggest that humidity levels across the Midwest have increased in recent decades. For example, Gaffen and Ross (1999) reported positive trends of both relative and specific humidity across the USA, although the relative humidity trends were weaker than specific humidity trends. Dai (2006) found relatively large changes of 0.5-2.0% per decade in surface relative humidity observations from 1976 to 2004 across the central USA while Changnon et al. (2006) reported a steady increase of the frequency of high dewpoint days during the period 1960-2000. In a very recent study, Schoof (2012) found increases in maximum dew point temperatures during the summer season across the Midwest which partially offset flat or decreasing maximum air temperatures and a wide variance in trends of resulting apparent temperatures. A likely cause of higher dew point temperatures during the growing season is the significant increase in plant density from earlier decades, which greatly enhances the transpiration of water from the soil to the atmosphere (Changnon et al. 2003).

Wind

Similar to humidity, there is a relative paucity of long-term records of near-surface wind speeds, which when coupled with inconsistencies manifest in different data sets, the highly uneven spatial coverage of surface observing stations, and issues pertaining to local land-cover change in the proximity of the observational sites, confound accurate assessment of wind climates and the presence or absence of temporal trends. In an analysis by Pryor et al. (2009b) based on North American Regional Reanalysis (NARR) 8-times per day output,10m wind components at a resolution of ~ 32 × 32 km were extracted for 1979-2006 and analyzed to quantify mean temporal trends in a range of metrics of the wind speed distribution. In general, there was no evidence of significant changes in either the central tendency or higher percentiles of the wind speed distribution over the period of record.

Extreme Precipitation

Intense precipitation events are an important part of annual hydrology in the Midwest, with over 30% of total annual precipitation obtained in the ten wettest days of the year in most areas of the region (Pryor et al., 2009a). In the western part of the region, as much as 50% of annual accumulated precipitation is falls in 10 daily events. Spatial patterns in the total amount of precipitation in the 10 greatest rainfall events per year and in the temporal trends of that sum are given in Figures 7a and b (from Pryor et al., 2009a). Both metrics closely mirror those present in the total annual precipitation with the highest values in the south of the region and lowest values in the north. In general, stations that exhibit significant changes in the metrics of extreme precipitation indicate trends towards increased values. Twenty-two percent of the stations considered in the study exhibited significant increases in the total accumulated precipitation during the top-10 wettest days of the year. Over the region as a whole, the occurrence of intense precipitation events has risen substantially in recent decades. In an update of an earlier study by Kunkel (2003), the number of 24 hour, once in 5-yr storms was found to have increased by about 4% per decade since the beginning of the 20th Century (Figure 8). About 85% of the events occured during the warm season period of May through September and approximately 90% of the annual trend was due to increases during the warm season period. Synoptically, the risk of intense rainfall events in the region tends to be associated with a westward extension and strengthening of the Bermuda subtropical high across the western Atlantic Basin (Weaver and Nigam, 2008; Bell and Janowiak, 1995) as well as the development of a slow moving, cut-off-low system over the Rockies Mountain and Great Plain region which and steadily advexcts low-level moisture into the Upper Mississippi region from the Gulf of Mexico (Gutowski et al., 2008). The trend towards heavier rainfall has resulted in an overall increased flooding threat across the region (Markus et al., 2007), although in many urban areas the increased flood risk was found to be more strongly associated with land cover change factors than climatologic factors (Scharffenberg and Fleming, 2006).

Extreme Temperatures

Time series plots of 4-day cold waves and heat waves in the region from 1985 through 2010 are given in Figures 9 a and b after Kunkel (2003). Following relatively higher frequencies during the first few decades of the 20th century and from the late 1960's through the early 1990's, intense cold waves have been relatively infrequent. The frequency of intense heat waves has also been relatively low in recent decades, especially relative to the 1930s Dust Bowl era which remains the most intense in the historical period of record.

Given recent upwards trends in temperature overall, a majority fraction of climate observing sites within the region recorded significant increases in warm extreme maximum temperature exceedences during the 1960-1996 period as well as increases in warm minimum temperatures and decreases in cold extreme maximum and minimum temperature exceedences (DeGaetano and Allen, 2002).

Drought

Given an increase in precipitation across the region during the past several decades, the incidence of drought has decreased with time. In a study across central sections of the Midwest, Mishra et al. (2010) found upward trends of precipitation and temperatures from 1916-2007 were associated with increases in total column soil moisture and runoff and decreases in frozen soil moisture. The authors also concluded that the study region has experienced reduced numbers of extreme and exceptional droughts with lesser areal extent in recent decades. A study by Andresen et al. (2009) suggests that a majority of the 10-15% increase in annual precipitation in Michigan during the past 50 years ended up as shallow aquifer recharge, which is in turn supported by observations of increasing base streamflow across the region (Johnston and Shmagin, 2008). The trend towards a wetter climate and decreasing drought frequency has also had a major impact on the region's agriculture industry in recent decades, with relative increases in crop yields due to less moisture stress and overall more favorable growing conditions (Andresen et al., 2001; Kucharik and Serbin, 2008).

- Synoptic Changes

The physical causes behind the trends noted in this study are in many cases unclear. However, given the strong dependence of daily and weekly weather patterns in the region on the location and behavior of the polar jet stream, it is likely that they are at least partially linked to larger, synoptic-scale changes of this feature. In general, synoptic patterns characterized by large amplitude long waves in the middle and upper levels of the hemispheric circulation across the region lead to cooler or warmer than normal weather, and depending on the location of the upper air feature, wet or dry conditions resulting from cyclones or anticyclones, respectively. While several studies have investigated links between climatologic trends and synoptic circulation patterns over large scale areas, relatively few have focused on the Midwest region.

In a study over the Northern Hemisphere, Agee (1991) found a positive correlation between increased (decreased) cyclone frequency and increased (decreased) hemispheric temperatures associated periods of warming and cooling mean temperatures between from 1900-1990. He associated the periods of warming with a flatter, relatively zonal pattern jet stream of short waves carrying more numerous yet weaker disturbances, and periods of cooling with stronger, less numerous disturbances.

There are documented changes in synoptic patterns over at least portion of the Midwest. In a study over the Great Lakes region, Angel (1996) found a statistically significant increase in the frequency of strong cyclones over the Great Lakes in November and December during the 20th century. This is consistent with a subsequent study by Polderman and Pryor (2004), who reported an increasing frequency of cyclones originating from Colorado and surrounding region along with a decrease in the frequency of Arctic (cold polar highs) outbreaks in the Great Lakes region during their 1956-1999 study period. However, the link between upper tropospheric flow and anomalous weather trends in the region is complicated. For example, Booth et al (2006) linked enhanced westerly upper air flow during the summer with increases in the frequency of relatively dry Pacific-origin air masses, reductions in northward Gulf of Mexico moisture transport, and to drier than normal conditions across western sections of the Midwest region. On the other hand, Grover and Sousounis (2002) suggest that upper tropospheric flow across the region during the fall season was relatively more meridional during the 1935-1956 period, and more zonal during the 1966-1995 period, which may have led to both greater frequency and total amounts of precipitation. In this study, the zonal flow was associated with greater baroclinicity across the Rocky Mountain region as well as a stronger subtropical jet and stronger low-level flow of moisture from the Gulf of Mexico. Some trends appear to also be related to longer term large scale oceanic sea surface temperature and circulation patterns in the Pacific and/or Atlantic Basins (e.g. Birka et al., 2010; McCabe et al., 2004).

Summary

Climate across the Great Lakes region has varied markedly during the past, ranging from tropical to glacial and including almost everything in between. Instrumental measurement records of the most recent century suggest some general temporal trends across the region. Mean temperatures warmed from approximately 1900 to 1940, followed by a cooling trend from the early 1940's to the late 1970's, followed by a second warming trend that began around 1980 through the present. Much of the warming trend during the past 2-3 decades has been associated with warmer minimum temperatures during the winter, spring, and summer seasons. Following an abnormally dry decade during the 1930's, the region has also progressively become wetter, due both to increases in the number of wet days and intense precipitation events. Seasonal snowfall has trended upwards in areas of the region frequented by lake-effect snowfall, while totals have remained steady or decreased slightly in non-lake effect areas. Given milder winter temperatures, snow cover is decreasing across the region, even in areas where snowfall has increased. Trends of severe weather vary across the region, with general decreases in the frequency of hail and increases in frequency of heavy rain events and associated flooding.

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Tables

	Precipitation (in./year)					Temp (ºF/year)				
1895-2010	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
IA	0.040***	0.002	0.017***	0.020***	0.000	0.009**	0.014	0.014**	0.004	0.001
IL	0.039***	0.004	0.012	0.012*	0.010	0.004	0.005	0.011*	-0.001	-0.001
IN	0.049***	0.001	0.015*	0.020***	0.012	0.003	0.006	0.010*	-0.005	-0.001
MI	0.038***	0.003	0.004	0.016***	0.016***	0.001	0.008	0.007	-0.006	-0.008
MN	0.029***	0.003	0.008	0.008	0.010*	0.014***	0.022*	0.015**	0.008*	0.006
MO	0.027	0.005	0.010	-0.004	0.015*	0.005	0.008	0.010*	0.002	-0.004
OH	0.034***	-0.002	0.011*	0.008	0.015***	0.008***	0.011	0.014***	0.002	0.003
WI	0.022**	0.002	0.005	0.012*	0.003	0.009***	0.019*	0.013*	0.002	0.002
AVG	0.035	0.002	0.010	0.012	0.010	0.007	0.012	0.012	0.001	0.000

	Precipitation (in./year)					Temp (ºF/year)				
1981-2010	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
IA	0.075	0.031	0.044	0.079	-0.081*	0.007	-0.031	-0.010	-0.006	0.062
IL	0.078	0.029	0.053	0.051	-0.053	0.036	0.014	0.046	0.020	0.050
IN	0.196*	0.073	0.066	0.069	-0.011	0.033	0.005	0.058	0.016	0.040
MI	0.000	0.040	0.033	0.006	-0.076**	0.041	0.036	0.018	0.030	0.081***
MN	0.016	0.028**	0.023	-0.025	-0.003	0.028	0.007	-0.037	0.005	0.122***
MO	0.014	-0.007	0.073	0.013	-0.065	0.038	0.020	0.035	0.045	0.043
OH	0.222**	0.084***	0.066	0.057	0.017	0.042*	0.008	0.060	0.048	0.047
WI	-0.005	0.033	0.035	0.033	-0.104 ***	0.037	0.030	-0.005	0.015	0.100***
AVG	0.075	0.039	0.049	0.036	-0.047	0.033	0.011	0.021	0.022	0.068

Table 1 a, b. Yearly trends in precipitation (inches/year) and mean temperature (ºF/year) for a) 1895-2010 and b) 1981-2010 periods. Asterisks denote significance at 0.10 (*), 0.05(**), and 0.01(***) levels respectively.

Figures

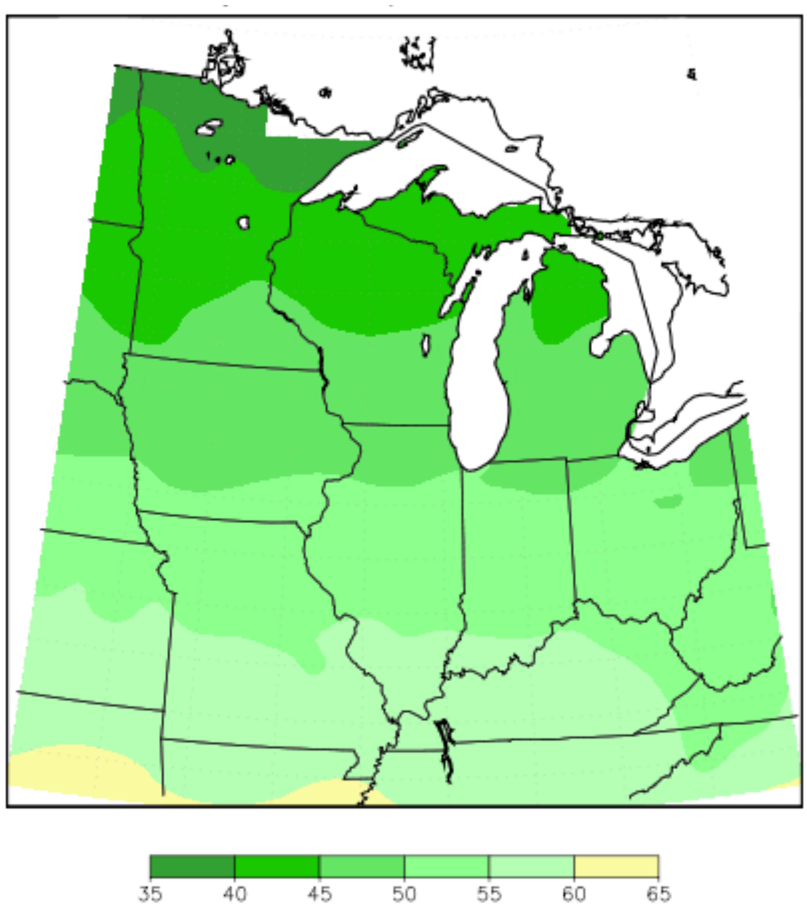

Figure 1. Average annual temperature (°F), 1981-2010. Figure courtesy of Midwestern Regional Climate Center.

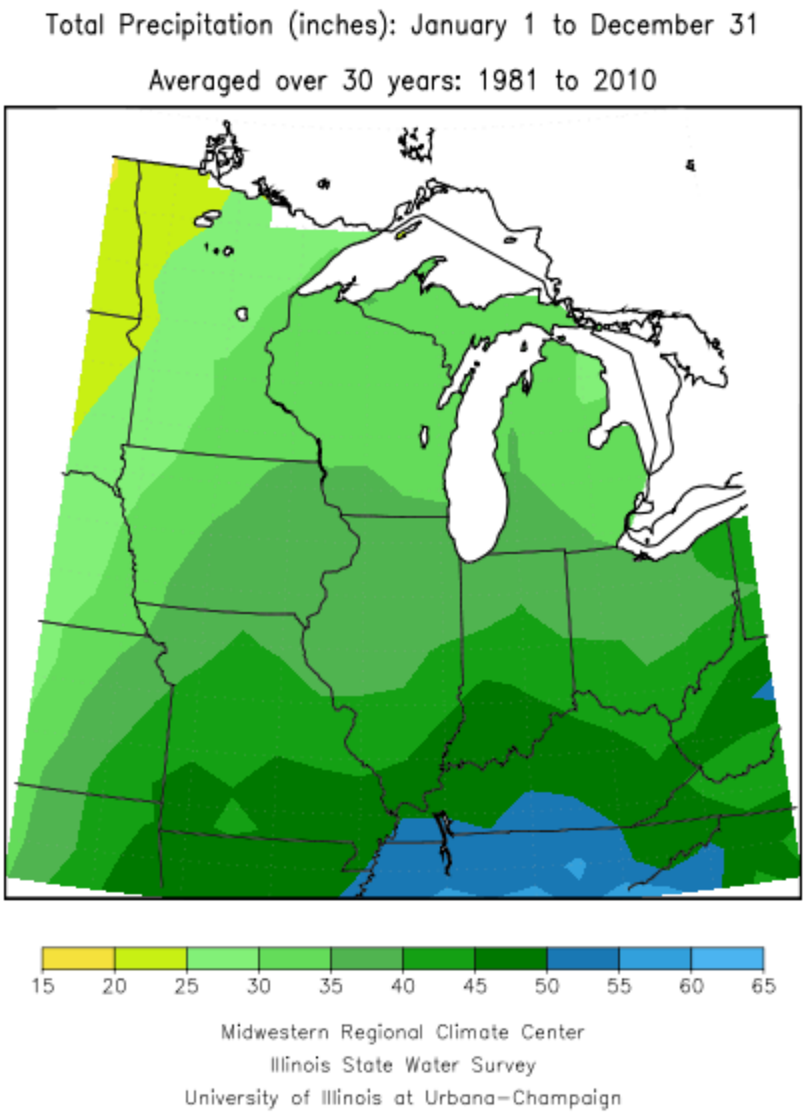

Figure 2. Average annual precipitation, 1981-2010. Figure courtesy of Midwestern Regional Climate Center.

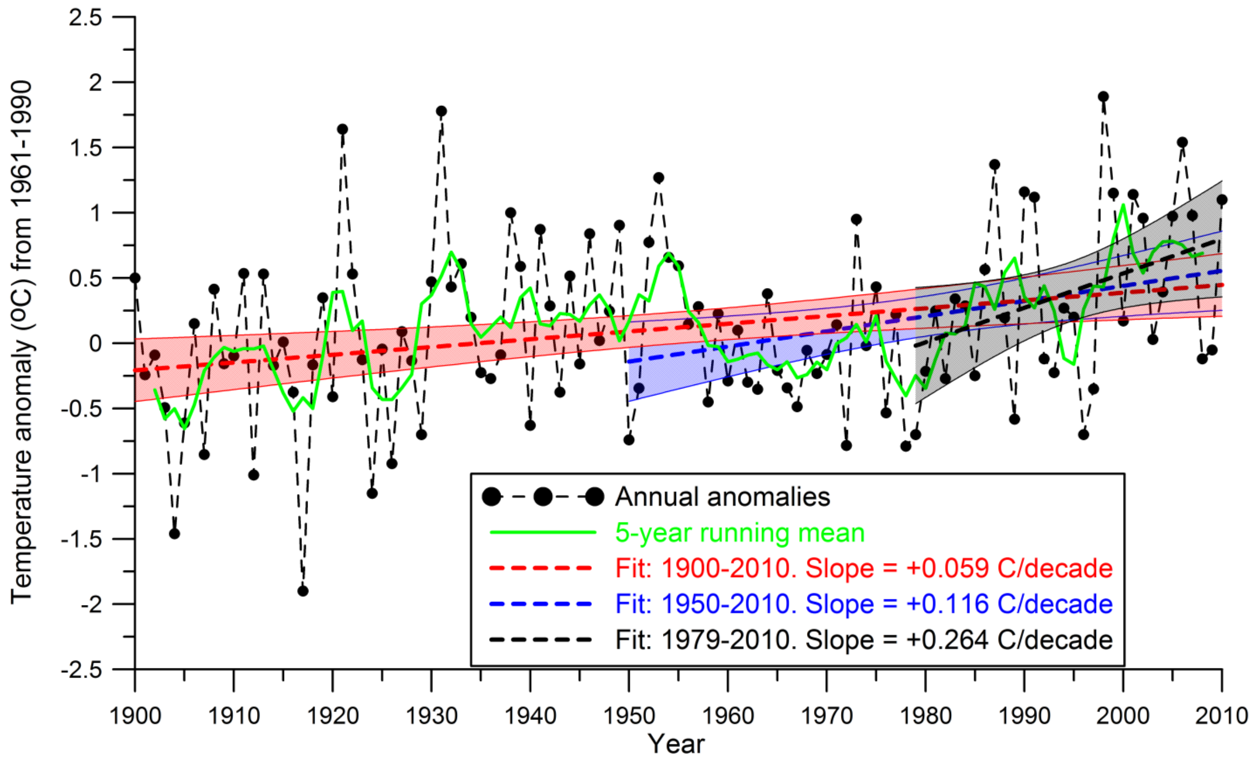

Figure 3: Annual temperature anomalies for the Midwest from the CRUTEM3 data set. The anomalies are relative to 1961-1990. The data have a spatial resolution of 5 x 5° thus the domain used to construct this figure is 35°N to 50°N and 95°W to 80°W. Data were downloaded from http://www.cru/uea.ac.uk/cru/data/temperature/#datdow. Also shown is a 5 year running mean and linear fits to the annual data for 1900-2010, 1950-2010 and 1979-2010. The shading represents the 95% confidence intervals on the fits. The slopes of the region-wide trend estimates are expressed in °C per decade and are shown for 3 time periods; 1900-2010, 1950-2010, and 1979-2010 (Pryor and Barthelmie 2012a).

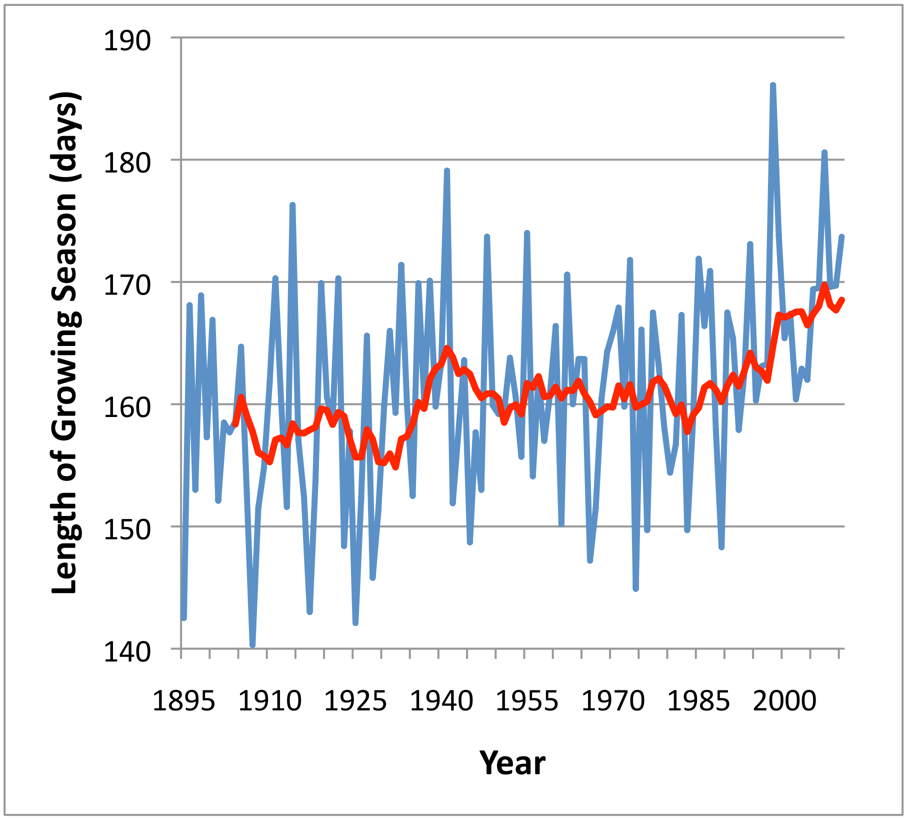

Figure 4. Length of the growing season, defined as the period between the last occurrence of 32° in the spring and first occurrence of 32°F in the fall. The red line is a 10-yr moving average. Based on data from the National Climatic Data Center for the cooperative observer network and updated from Kunkel et al. (2004).

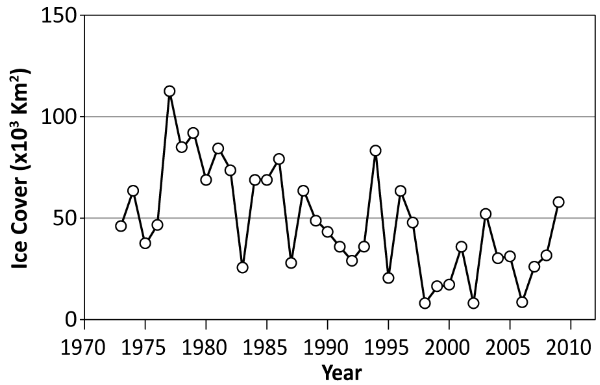

Figure 5. Time series of annual average ice area coverage on the Great Lakes. From Wang et al. (2010).

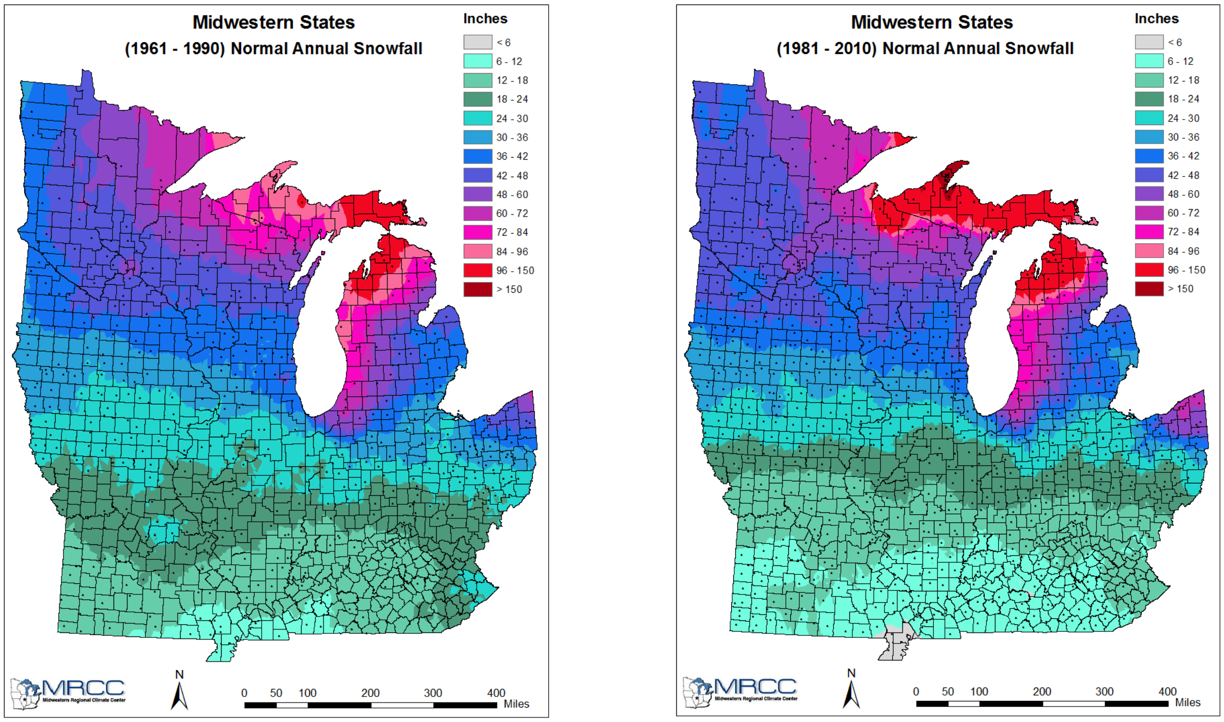

Figure 6. Mean seasonal total snowfall (inches) across the Midwest for a) 1961-1990 (left) and b) 1981-2010 (right) periods. Figures courtesy of Midwest Regional Climate Center.

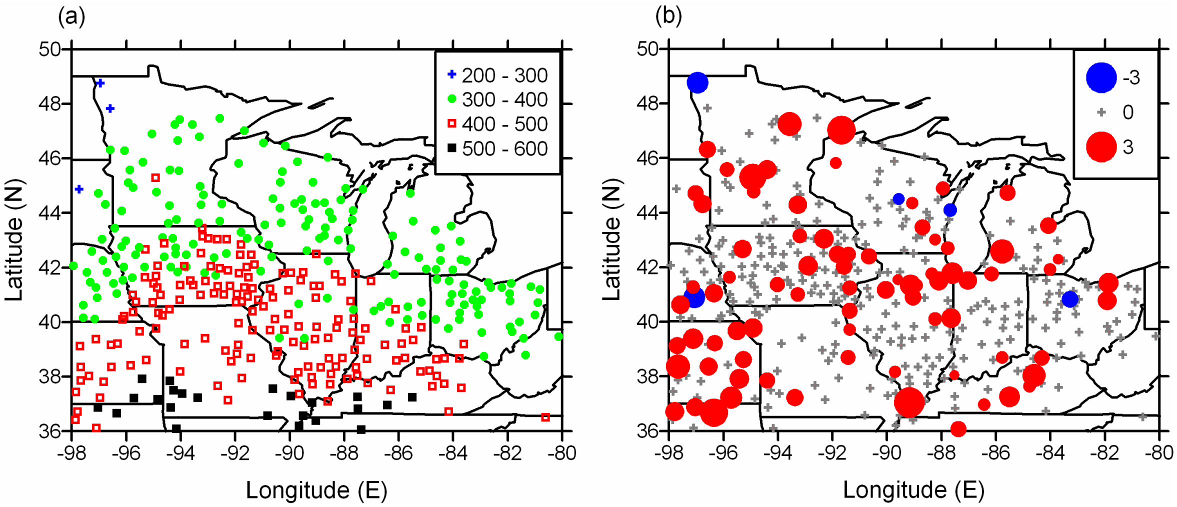

Figure 7. a) Mean sum of the top-10 wettest days in a year (mm) (1971-2000) and b) Trend in sum of the top-10 wettest days in a year 1901-2000 expressed in a percent per decade. Red circle indicates the station showed a statistically significant increase through time; blue circle indicates a statistically significant decline. Plus symbol indicates trend was not significant (shown as 0 in the legend. The diameter of the dot scales linearly with trend magnitude (Pryor et al. 2009b).

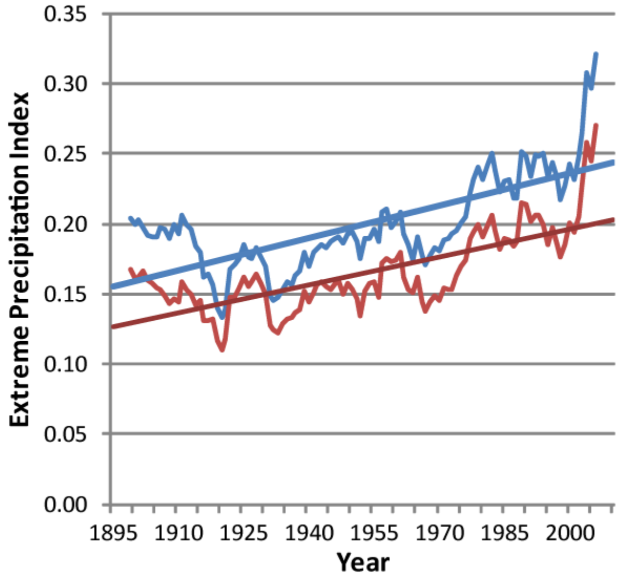

Figure 8. Time series of extreme precipitation index for the occurrence of 1-day, 1 in 5 year extreme precipitation events. The annual time series and linear trend (straight line) are shown in blue. A time series for the months of May through September is shown in red. Analysis is averaged for the states of IL, IN, IA, MI, MN, MO, OH, and WI. Based on data from the National Climatic Data Center for the cooperative observer network and updated from Kunkel et al. (2003).

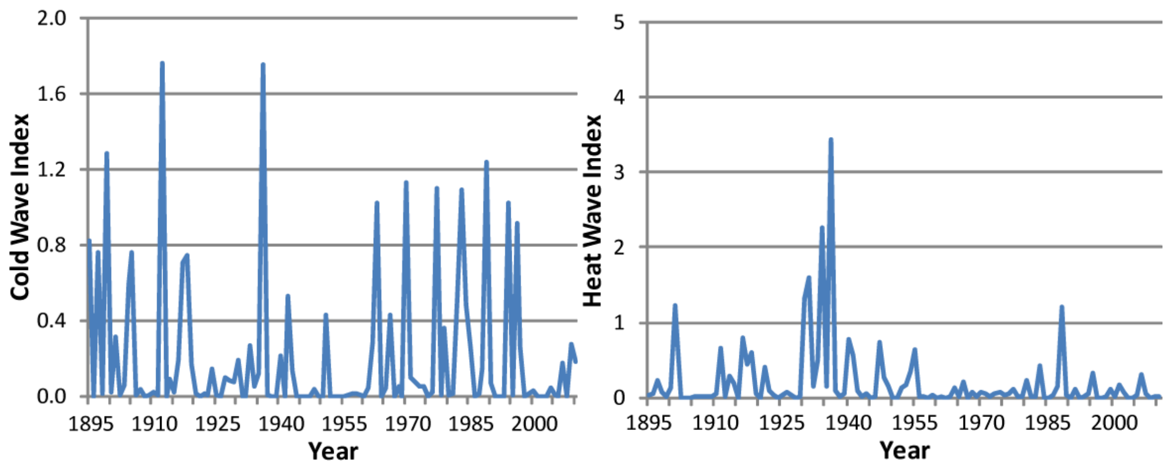

Figure 9. Time series of an index for the occurrence of a) cold waves defined and b) heat waves defined as 4-day periods colder and warmer than the threshold for a 1 in 5 year recurrence, respectively. Based on data from the National Climatic Data Center for the cooperative observer network and an update by Kunkel et al. (1999).

Climate Projections for the Midwest: Availability, Interpretation and Synthesis

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Abstract/Highlights

Climate projections from multiple sources display good agreement regarding future changes for the Midwest region in annual and seasonal mean temperature, the frequency of temperature thresholds such as the frequency of heat waves, and the magnitude of temperature indices such as degree day accumulations. Comparison and integration of the different downscaled temperature projections also illuminate interesting and relatively consistent spatial variations in projected future temperature change across the Midwest. In contrast, projections of future precipitation change remain highly uncertain for the Midwest. The majority of climate projections are in agreement regarding the sign of the projected change for only the winter (December-February) season. Precipitation intensity is generally projected to increase by the mid and late century, although errors in the downscaled simulations of the frequency distribution of daily and subdaily precipitation complicate interpretation of potential changes in intensity. Uncertainty also shrouds future projections in wind climates. The dynamically-downscaled climate projections available from North American Regional Climate Change Assessment Project provide an exciting new resource for assessment studies, although evaluation of these projections for the Midwest region remains limited. Preliminary elevations suggest that bias corrections may be needed for some applications.

Introduction

Climate change projections, sometimes referred to as climate scenarios, are widely used in climate change impact assessments, including assessments conducted at the local/regional scale such as the scale of the National Climate Assessment Midwest region. Often, although not always, local/regional climate impact analyses employ an end-to-end assessment that links the climate projections in a sequential manner to a downstream suite of models which may include, but are not limited to, ecological/process models, economic models, and decision making models (Winkler et al., 2011a; Figure 1).

Figure 1. Schematic of an end-to-end assessment strategy, also referred to as a "feed forward approach", for a local/regional climate impact assessment. The types of models and the number of "links" will vary for different assessments. Climate change projections serve as a starting point for an end-to-end assessment. SOURCE: Modified from Winkler et al. 2011a. [Permission needed.]

A number of different approaches are used to develop climate projections. Impact researchers must carefully consider the strengths and limitations of these approaches along with the characteristics of the ensuing climate projections when selecting projections for use in a specific application. Furthermore, syntheses of potential impacts for a region, including the whitepapers prepared by the Midwest Technical Input Team and the Midwest Chapter for the National Climate Assessment (NCA) report, must take into consideration the characteristics and limitations of the different sources of climate projections when interpreting, comparing, and integrating outcomes from multiple studies and impact analyses.

The goals of this whitepaper are multi-fold. First, we briefly review commonly-used approaches to develop local/regional climate projections and highlight strengths and limitations. Second, available climate projections for the Midwest region are summarized to provide an indication of currently-available resources for climate change assessments for the region. Third, we discuss several key concepts and issues related to climate change projections whose understanding we feel is essential for an informed and nuanced interpretation and synthesis of the substantial literature on potential climate impacts in the Midwest. Fourth, we summarize by climate variable potential future changes as synthesized from currently-available peer-reviewed and gray literature. This whitepaper expands upon the document, "Climate of the Midwest U.S.", prepared by Kunkel et al. (2012) for the National Climate Assessment Development and Advisory Committee, in that additional climate projections are incorporated and background information for thoughtful use of these projections is provided.

Climate Projections: Downscaling Methods

Typically, climate change projections are derived from simulations from global climate models (GCMs). GCMs have a relatively coarse spatial resolution; those used for the IPCC Fourth Assessment Report had latitude-longitude spacing that ranged from 4^{o} by 5^{o} to about 1.1^{o} by 1.1^{o}. This motivates the use of "downscaling" methods to infer the high spatial and/or temporal resolution needed for most impact assessments.

Traditionally, downscaling procedures have been classified as either "dynamic" or "statistical". However, following Winkler et al. (2011a,b), we employ a three-tier classification, namely dynamic downscaling, empirical-dynamic downscaling and disaggregation downscaling methods. In our opinion, this classification of downscaling methods better captures the underlying philosophies of the different downscaling approaches, and the terminology helps point to the characteristics, and also the limitations, of the resulting climate projections. Each of the three downscaling methods is briefly summarized below and illustrated in Figure 2. More detailed reviews of downscaling approaches can be found in Mearns et al. (2003), Wilby et al. (2004), Benestad et al. (2008), and Winkler et al. (2011a,b). Additionally, Winkler et al. (2011a) provide a "checklist" of considerations for evaluating alternative downscaling options.

It is not possible to argue for one downscaling approach as universally "better" than another (Christensen et al. 2007). Rather, the different approaches should be viewed as complementary, and the choice of downscaling approach(s) should be appropriate to the assessment objectives.

Dynamically-downscaled climate projections

Dynamic downscaling refers to the use of numerical models such as regional climate models (RCMs) to simulate fine-resolution climate fields. Dynamic downscaling can be particularly useful when the local/regional climate is strongly influenced by mesoscale (a few to several hundred kilometers) circulation features whose strength and/or location may change in a perturbed climate or when regional-scale influences such as terrain or changing land use are anticipated to have large effects on the local/regional climate. RCMs, like GCMs, are based on the fundamental equations of atmospheric dynamics and thermodynamics. For this reason they are often a better choice when an assessment requires a suite (e.g., temperature, humidity, wind, and radiation) of physically consistent and spatially and temporally coherent climate variables (Hanssen-Bauer et al. 2005). However, dynamic downscaling is demanding in terms of time and resources, particularly when a very fine resolution is desired. For comparison to observations RCMs are driven by lateral boundary conditions obtained from reanalysis fields, in which a GCM is constrained to follow observations. The reanalysis is considered to represent a "perfect" (more correctly, the best possible) GCM and thus allows the errors and biases of the RCM itself to be isolated. RCMs are also driven by coarse-scale simulations from GCMs both for historical and future periods. Comparisons of RCM results when driven by historical reanalyses with corresponding results when driven by GCM simulation of the corresponding period help to determine errors attributable to using the GCM's depiction of current climate to force the downscaled results. Typical horizontal resolutions of RCMs for multi-decadal, continental-scale simulations are on the order 25-50 km (Rummukainen 2010). Simulations with resolutions of only a few kilometers are possible using multiple nested RCMs, or when considering shorter periods or smaller domains (e.g., Liang et al. 2001; Hay et al. 2006).

Resource constraints often limit RCM simulations to relatively short periods of a few decades in length (e.g. Christensen et al. 2002; Leung et al. 2004; Plummer et al. 2006). Furthermore, simulations with a given RCM typically have been driven by a single GCM or only a small number of GCMs. This limitation arises from several practical considerations: GCMs do not usually store the high time resolution data needed for RCM boundary conditions; the differing output formats for different GCMs require extensive coding or data reformatting so that the data can be read by the input procedures used in the RCMs; and execution of RCMs requires substantial computing time and human resources. Both short simulation periods and limited number of GCMs used in RCM studies have implications for evaluating the uncertainty surrounding projected changes. These constraints may be ameliorated in future RCM simulations that use the CMIP5 GCM results currently being produced. The CMIP5 protocol includes provision for saving output from participating GCMs at sufficient time resolution for use as RCM boundary conditions so that suitable output from more GCMs will be available. The CMIP5 GCMs also use a standard output format which should reduce the effort needed to adapt an RCM to boundary values from different GCMs.

Another important consideration when interpreting dynamically-downscaled climate projections is that (as with GCMs) some processes either occur at scales finer than the RCM resolution or are too complex to be realistically represented within the model (Laprise 2008). These processes are instead "parameterized", i.e., represented in terms of resolved variables and/or simplified parameters. A variety of parameterization schemes exist for processes such as moist physics and land surface processes, and the choice of model parameterization may have a substantial impact on the RCM simulations (Liang et al. 2004).

An example of dynamic downscaling is the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2012), which has generated a uniquely detailed suite of regional-scale climate output. Under NARCCAP, RCMs have been driven both by reanalysis fields and by GCM results. In the former the lateral boundary conditions are supplied by output from the NCEP-DOE reanalysis (shown as NCEP in Table 1), while in the latter a suite of 4 GCMs has been used to provide the nesting. Output is being made available to all parties and for many variables at a daily or higher temporal resolution. This matrix of GCM-RCM combinations allows for detailed evaluation of the value-added of dynamical downscaling and the primary sources of uncertainty (Pryor et al. 2012b).

Table 1: Available NARCCAP simulations. SOURCE: http://www.narccap.ucar.edu/

Regional Models	**Climate Models**				
	GFDL	CGCM3	HADCM3	CCSM	NCEP
CRCM		X		X	X
ECP2	X		X		X
HRM3	X		X		X
MM5I			X	X	X
RCM3	X	X			X
WRFG		X		X	X
Time Slices	X			X	
ECPC					X
WRFP					X

Empirical-dynamic downscaling

Empirical-dynamic downscaling employs statistical methods to relate local/regional climate variables to large-scale circulation and atmospheric state variables that are chosen to represent important dynamical and physical processes in the atmosphere (Winkler et al. 2011a). Empirical-dynamic downscaling does not operate directly on the variable of interest as predicted by the global model, typically a surface weather variable such as temperature, precipitation or wind speed. Instead, the variable is inferred from derived relationships to large-scale variables predicted by the model. For example, precipitation could be inferred from the value of a mid-atmospheric circulation property such as vorticity (Schoof et al. 2010). This method is frequently used when climate scenarios for individual locations are required and/or when the climate variables needed for the assessment are poorly simulated by GCMs or RCMs. Also, because these methods generally are not as resource intensive as dynamic downscaling, it is somewhat easier to build a larger ensemble (i.e., suite) of projections and include multiple future time slices.

The underlying assumptions of empirical-dynamic downscaling are that 1) GCMs better simulate circulation and "free atmosphere" variables compared to surface climate variables, 2) circulation and free atmosphere variables are representative of larger spatial scales compared to surface climate variables, 3) empirical relationships can implicitly capture the effects of local topography, geography and boundary conditions on the surface variables, and 4) the relationships are stationary in time; i.e., relationships observed for the current climate will be applicable in the future (Winkler et al. 1997). Statistical transfer functions are developed to relate these large-scale variables to surface weather elements such as temperature and precipitation. Downscaled projections usually are developed separately for each climate variable, which results in less physical consistency and spatial and temporal coherency between variables as compared to scenarios obtained from dynamic downscaling. Climate projections can be developed using this approach at temporal resolutions ranging from daily to seasonal. Many empirical-dynamic downscaling approaches are patterned after short-range forecasting techniques such as model output statistics (MOS; Karl et al. 1990). Regression-based methods are commonly used to develop empirical relationships between the circulation-based predictors and the surface-based predictands though other methods such as neural networks also have been explored (Schoof and Pryor 2001; Olsson et al. 2004).

The empirical functions are typically developed separately for each location, in order to implicitly capture local influences.

Disaggregation downscaling methods

Disaggregation methods include interpolation and other statistical methods to estimate fine-scale values from coarse-scale spatial fields of a particular variable, or to infer finer time resolution from temporally-aggregated averages or accumulations of climate variables (Winkler et al. 2011a). To date, disaggregation downscaling has been the most common approach for developing local/regional climate projections. In general, disaggregation methods require fewer resources than either dynamic or empirical-dynamic downscaling, contributing to their popularity.

A simple approach that incorporates both spatial and temporal disaggregation is to 1) spatially interpolate coarse-scale GCM simulations of monthly means and accumulations of climate variables to a finer resolution grid or to station locations, 2) calculate the difference or ratio between the GCM projected value for a future period and for a control (historical) period, and 3) apply the differences (for temperature) or ratios (for precipitation) to gridded or station specific historical observed time series. This approach, referred to as the "delta method," was one of the first downscaling methods employed in climate impact assessments and remains popular today. The spatial interpolation schemes vary from those based on distance only (e.g. Tabor and Williams 2010) to more complex schemes such as thin plate spline interpolation (e.g. WorldClim future projections, http://www.worldclim.org/futdown.htm) that uses elevation (obtained from a digital elevation model) in addition to latitude and longitude to capture the influence of fine-scale topography on the temperature and precipitation fields. The advantages of this downscaling approach, beyond simplicity, are that the daily series are temporally and spatially coherent as long as the same historical series for the same time period was used for all locations when applying the delta change value. Among the disadvantages are that the resulting fields are not spatially consistent and that changes in the statistical distributions of events are not accounted for (e.g., decreased or increased frequency of storms resulting from shifts in the jet stream). A variation of the delta approach is to first apply bias corrections to the GCM-simulated means and accumulations to adjust for error observed in the GCM simulations for historical periods.

Stochastic weather generators (e.g. Wilks 1992; Katz 1996; Semenov and Barrow 1997; Dubrovsky et al. 2004, Qian et al. 2008; Semenov 2008) are an alternative approach to obtaining finer temporal resolution from monthly projections. Typically, weather generators use Markov processes to simulate wet/dry days and then estimate wet day amounts, temperature and solar radiation conditional on precipitation occurrence (Wilby et al. 2004; Wilks 2010). One consideration when employing climate projections developed using weather generators is that the daily values are not spatially and temporally coherent.

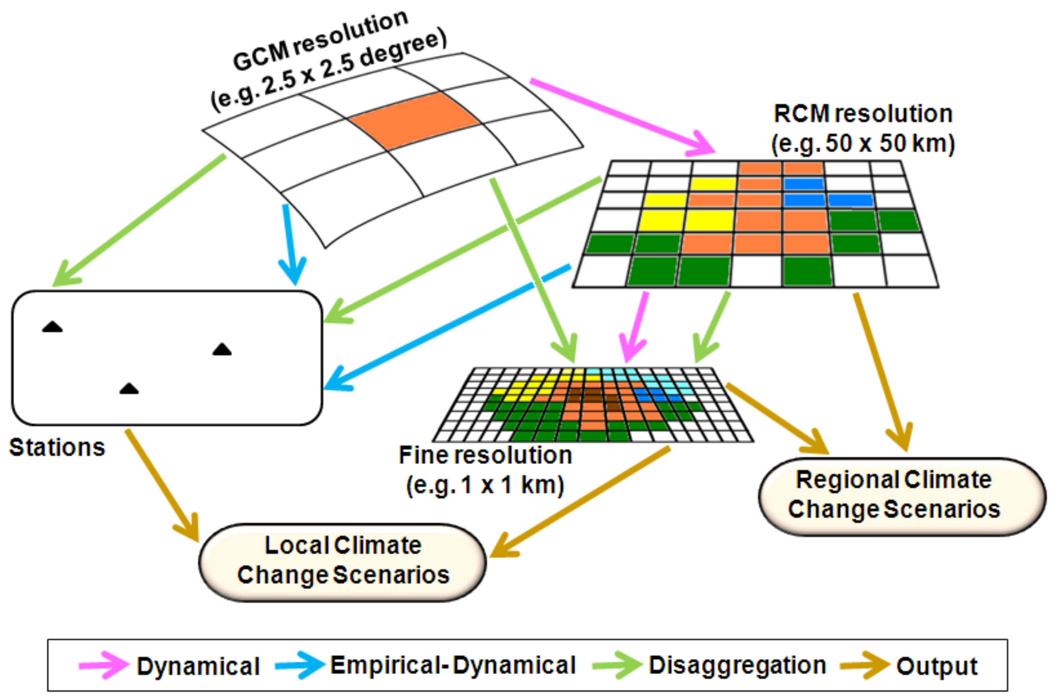


Figure 2: Schematic of the outputs of dynamic downscaling, empirical-dynamic downscaling, and disaggregation downscaling methods when applied to GCM simulations. The products from the downscaling can be gridded fields of climate variables at a range of spatial scales or climate scenarios for specific locations. Different approaches to downscaling can be applied, as shown by the colored arrows. Also, multiple downscaling steps can be used to obtain the desired spatial resolution. SOURCE: Winkler et al., 2011a. [Permission needed.]

Available Climate Change Projections for the NCA Midwest Region

In the support documents provided by Kunkel et al. (2012), four sets of climate projections are utilized. These include: 1) coarse-scale simulations from fifteen GCMs obtained as part of the Climate Model and Intercomparison Project Phase 3 (CMIP3; Meehl et al., 2007), 2) time series of monthly temperature and precipitation at a 1/8^{o} latitude/longitude resolution obtained by applying combined bias correction and spatial disaggregation downscaling procedures, referred to as the "BCSD method" (Maurer et al. 2007) to the CMIP3 GCM simulations, 3) daily time series of temperature and precipitation obtained from temporal disaggregation of the BCSD spatially downscaled monthly and temperature values by adjusting randomly-selected observed daily time series by the projected differences in the monthly values (i.e., the delta method), and 4) nine RCM simulations obtained from the North American Regional Climate Change Assessment Project (NARCCAP). Thus, the guidance provided to the National Climate Assessment includes one set of non-downscaled climate projections, two sets of projections downscaled using disaggregation approaches but with different temporal resolutions, and a set of dynamically-downscaled projections.

Considerable additional resources are available climate for change assessments for the Midwest region. A number of fine-resolution climate projections with global coverage have been developed by research groups worldwide that may be relevant for assessment activities in the Midwest depending on the assessment goals. Additionally, climate change projections have been developed specifically for the Midwest. Available climate projections are summarized in Table 2. As can be seen from the table, these projections differ in terms of downscaling procedure, resolution, time slices, the number of GCMs from which projections are derived, and the underlying greenhouse gas emissions scenarios.

Considerations when Using and/or Interpreting Climate Projections

Ensembles and multimodel means

One of the most robust conclusions from climate model evaluation studies is that there is no single best model for all locations, periods, or variables of interest (Pierce et al. 2009). Therefore, most climate change assessments employ an ensemble of climate projections. Ensembles provide an estimation of what Jones (2000) refers to as the "calibrated range of uncertainty", and what Stainforth et al. (2007, page 2166) refer to as the "lower bound on the maximum range of uncertainty". A typical ensemble will include projections derived from a number of different GCMs in order to capture uncertainty introduced by the structural differences of GCMs. Projections obtained from GCM simulations driven with different greenhouse gas emissions scenarios are also typically included in an ensemble. More recently, projections developed from multiple simulations from the same GCM, but where selected physical parameterizations are perturbed or where initial conditions have been slightly modified to evaluate variability, are included in an ensemble (Murphy et al. 2007). Less frequently, an ensemble includes projections derived using multiple downscaling methods. In most cases the choice of GCM introduces the largest degree of uncertainty to an ensemble (e.g. Benestad 2002; Winkler et al. 2003; Wilby and Harris 2006). An exception is dynamic downscaling where the use of multiple GCMs *and* multiple RCMs may be required, as some authors (e.g. Déqué et al. 2007) have reported that the choice of RCM can introduce as much uncertainty as the choice of GCM. A schematic illustrating the potential components of an ensemble of climate projections is shown in Figure 3.

Multimodel means, or in other words the average of the individual members, are frequently used to summarize an ensemble of climate projections, and indeed this is the approach used by Kunkel et al. 2012 in the NCA support documents. The motivation for this usage comes from medium range weather forecasting, where the ensemble mean has been shown on average to be a better prediction than the prediction of an individual member (Christensen et al. 2010). The most common method for producing the ensemble mean is to take the simple arithmetic average of all participating models. Alternative methods have been proposed in which the participating models are unequally weighted (e.g., Giorgi and Mearns 2003). However, recent research concluded 'we do not find compelling evidence of an improved description of mean climate states using performance-based weights in comparison to the use of equal weights' (Christensen et al. 2010). Transferring this concept to climate projections is hindered by the interdependence among the ensemble members (Tebaldi and Knutti 2007). Many GCMs and RCMs share the same or similar numerical schemes and parameterizations, and consequently scenarios developed from different climate models are not independent (Fowler et al. 2007). Ensembles developed using different downscaling methods are also not independent if the methods are applied to the same GCM. Because of this interdependence, consensus among projections should not be confused with skill or reliability (Maraun et al. 2010). Another situation where a multimodel mean may be misleading is when some members of an ensemble project a positive change in a climate variable while others project a negative change. In this case, the multimodel mean of the projected change can approach zero even though all of the ensemble members project a substantial change but of opposite sign. The near-zero ensemble mean may be interpreted as "no change" when an arguably more informative interpretation is that the nature of the change is uncertain. Precipitation projections tend to highly uncertain and often of opposite sign; thus, simple multimodel means may not be very informative in considering future changes in precipitation.

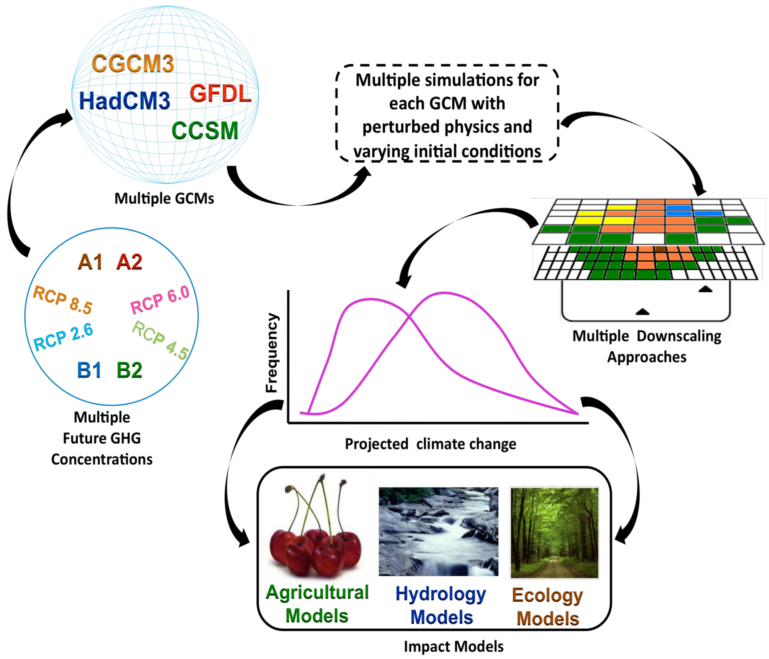


Figure 3. *Sources of uncertainty and possible distributions of an ensemble of projected local/regional climate change. The dashed line indicates uncertainty sources that are infrequently considered. SOURCE: Winkler et al. 2011b.* [Permission needed.]

"Shelf life" of climate projections

The NCA organizers have requested that any new analyses for the assessment utilize climate projections developed from IPCC AR4 era GCMs. On the other hand, the available peer-reviewed literature for a particular sector or region employs climate projections from older versions of GCMs in addition to more recent simulations. In fact, there is often a substantial lag between the release of new GCM simulations and the development of downscaled climate projections, and a further lag associated with the evaluation of the downscaled projections and their use in applications. Thus, much of the literature reviewed for the NCA will have employed simulations from earlier versions of GCMs. As pointed out by Winkler et al. (2011b), the common assumption is that once a newer version of a GCM is available scenarios based on the older version are obsolete. Against this view it can be argued that older model runs have an advantage in that they often have been extensively compared to observations. Thus the characteristics and limitations of older model runs are better understood than are those of newer models that have not been as thoroughly evaluated. Additionally, recent guidance from the IPCC (IPCC I Technical Support Unit, 2010) suggests that it may be appropriate to combine GCM simulations from different "eras" in an ensemble. Thus, it is appropriate to integrate outcomes from assessment studies that used climate projections developed from older versions of GCMs with those that employed scenarios developed from more recent GCM simulations.

Influence of regional topography or circulation on climate

Unique characteristics of a region need to be taken into consideration when interpreting local/regional climate projections. An example for the Midwest is the Great Lakes and the surrounding lake-modified climates. The Great Lakes are crudely represented in the GCMs; for example, in the HadCM3 model used in the IPCC Fourth Assessment Report, the lakes appear as a single water body (Figure 4). Consequently, simple spatial interpolation of GCM output to a finer-resolution grid or a location will result in climate projections that inadequately (if at all) capture the influence of the Great Lakes on the local climate. Dynamic downscaling using RCMs may not fully capture the effect of the lakes, as many RCMs do not include a lake module, and lake temperature is crudely estimated in some RCMs as the average of nearshore Atlantic and Pacific temperatures. In this situation, empirical-dynamic downscaling methods and some bias correction approaches can implicitly capture, at least partially, lake influences although the downscaled climate variables should be carefully evaluated against observations.

Another feature that needs to be considered when interpreting precipitation projections is that the western portion of the Midwest region frequently experiences a southerly low-level wind maximum known as the "low-level jet," especially at night during the warm season (Walters et al. 2008). These jets contribute to the transport of moisture into the region, and downstream convergence can act to initiate or sustain convective precipitation systems that propagate across the region. The low-level jet is poorly represented in some GCMs and RCMs, introducing uncertainty into warm season precipitation projections. The propagating mesoscale convective precipitation systems induced by the jet are poorly represented at typical RCM grid spacings (Anderson et al. 2007) and are absent in GCMs executed at typical climate scales.

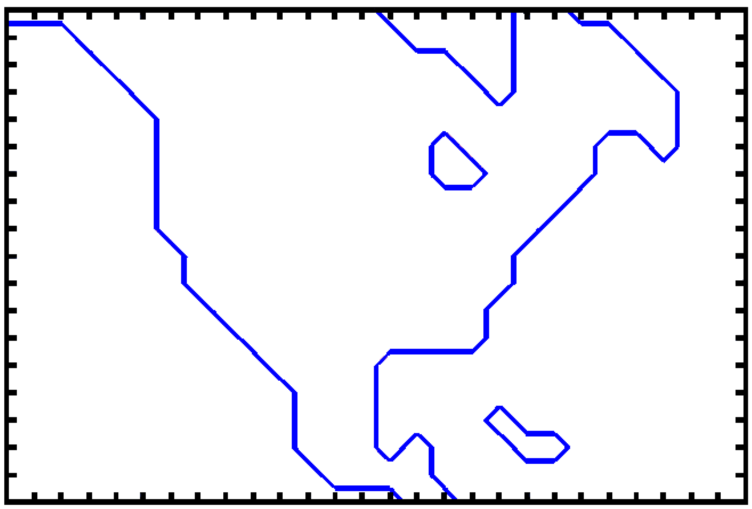


Figure 4: Land-sea mask for North America in the HadCM3 global climate model, one of the models used in the IPCC Fourth Assessment Report [Permission: Image generated by the authoring team and not published elsewhere; no permission needed]

Evaluation of Climate Projections

Evaluation is the responsibility of both the suppliers and the users of climate projections. Here we summarize recent attempts to evaluate GCM projections and RCM simulations available from NARCCAP. These examples were selected to illustrate evaluation techniques and strengths and weaknesses of climate projections. Although evaluation examples are provided for only one downscaling method (i.e., dynamic downscaling), evaluation is also a necessary step for empirical-dynamic and aggregation downscaling. An important consideration is that the evaluation needs to be conducted in light of the potential application, and the climate variables included in an evaluation should reflect the key concerns of the application. As an example, a recent evaluation of a empirically-dynamic downscaling procedure employed a large suite of precipitation metrics selected to represent future changes in precipitation thresholds and extremes including, among other, wet day probability, mean dry spell length, wet day precipitation intensity, and the 90th percentile of wet day precipitation (Schoof et al. 2010).

GCM simulations

Several studies have provided information on GCM performance relevant to the Midwest region. Ruiz-Barradas and Nigam (2010) examined precipitation over North America in four GCMs (CCSM3, GFDL CM2.1, HadCM3, and ECHAM5). They noted seasonal differences in regional precipitation biases, with the western U.S. generally being too wet in spring and the central U.S. being too wet in summer (except for CCSM3). They found that interannual variability of precipitation in the Great Plains region (which includes the western part of the Midwest region that is our focus) was generally similar to observed values, though the performance of each model was not necessarily consistent across seasons. The models varied in their ability to capture remote influences of sea-surface temperature on Great Plains precipitation, with CCSM3 failing to reflect the observed correlation with central Pacific sea-surface temperature. McCrary and Randall (2010) examined 20th century drought over the Great Plains in three GCMs (CCSM3, GFDL 2.0, and HadCM3). They found that all of the models produced excessive precipitation over the Great Plains. Simulated drought for the region was comparable to observations but the models differed in the nature of their drought forcing. While drought in GFDL CM2.0 and HadCM3 corresponded with low-frequency variations in sea-surface temperature, CCSM3 showed no significant correlation between precipitation and tropical Pacific sea-surface temperature (which is broadly consistent with the findings of Ruiz-Barradas and Nigam 2010). They suggest that drought persistence in CCSM3 may be related to local feedbacks arising from that model's tight land-atmosphere coupling.

In a more comprehensive study, Wehner et al. (2011) evaluated 19 models from CMIP3 focusing on their ability to reproduce observed temperature, precipitation, and drought incidence over North America as measured by the Palmer Drought Severity Index (PDSI). Results for the North American domain as a whole showed that all models underpredicted the areal extent of drought. Although Wehner et al. (2011) did not focus specifically on the Midwest, their computations of ensemble means across all models show that over most of the Midwest temperature bias is slightly negative while precipitation bias is small. As noted elsewhere ensemble means can hide substantial inter-model variability and the authors noted substantial variations in performance amongst the models. Diagnoses of PDSI from projections through the 21st century following the A1B emissions scenario showed that all models produced increases in the frequency and severity of drought. An interesting finding from their study is that much of the variability amongst the model projections, which often has been taken as a measure of uncertainty, results from differences in climate sensitivities amongst the models (i.e., projected temperature change for a given change in greenhouse gas concentrations). Variations in model projections for drought were lower when the models were referenced to a given temperature change rather than a given time period.

NARCCAP simulations

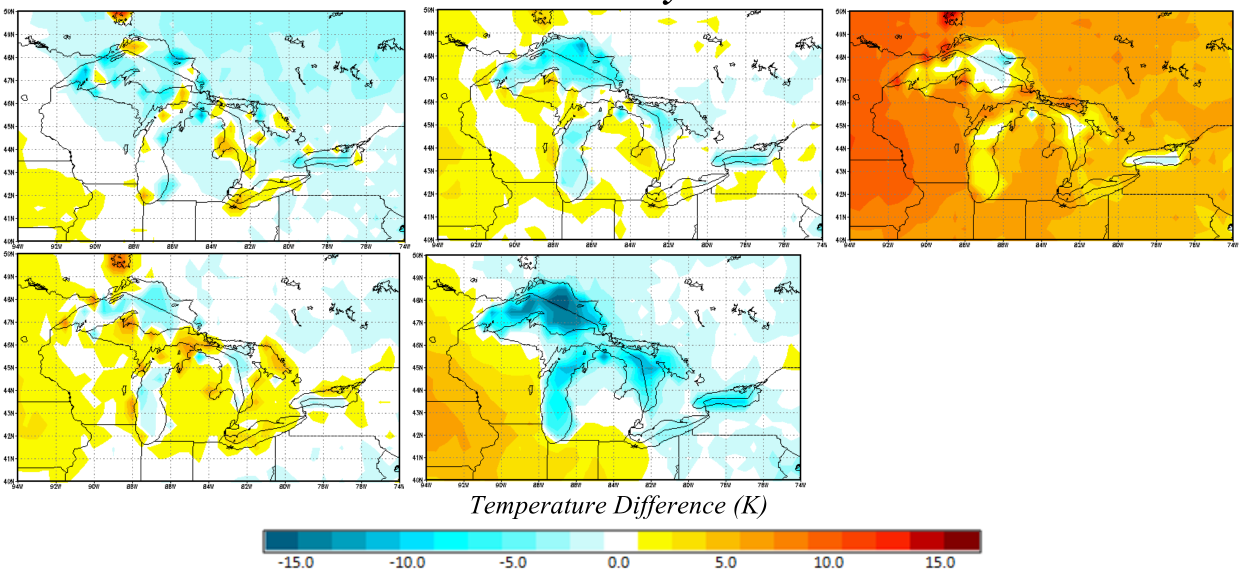
Evaluation of downscaled near-surface variables for a historical period can be used to assess the skill of the downscaling. Mearns et al. (2012) examined a variety of skill metrics for NARCCAP simulations of precipitation and temperature in current climate (1980-2004) using reanalysis fields as boundary conditions. Consistent with other studies they found there was no single best model across all metrics. There were suggestions of an advantage for regional climate models that use spectral nudging, in which the largest spatial scales of the boundary data are used to constrain the interior of the model domain as well as the boundaries.

Evaluations using the NARCCAP suite to simulate multiple descriptors of wind climates over the contiguous USA (Pryor and Barthelmie 2011, Pryor and Barthelmie 2012a, Pryor et al. 2012b) suggest that application of the RCMs improves the simulation of wind climates during 1979-2000 relative to the driving reanalysis and that the RCMs exhibit some skill in depicting historical wind regimes. Furthermore, evaluation of 50-year return period wind speed derived from the NARCCAP output for the historical period (1979-2000) relative to extreme wind speed estimates computed from station observed daily maximum fastest mile speeds at 35 stations across the contiguous USA revealed that the RCMs exhibit some skill in capturing the macro-scale variability of extreme wind speeds. Simulations of intense and extreme wind speeds by the RCMs were found, at least to some degree, to be independent of the lateral boundary conditions, instead exhibiting greater dependence on the RCM architecture. Although not employing NARCCAP simulations, a recent analysis of dynamically-downscaled wind speeds for a nominal height of 10 m with the lowest model level (approx. 70 m a.g.l.) from the Rossby Center RCM (RCA3) run at four resolutions (ranging from 50 × 50 km to 6 × 6 km) found that model resolution had the largest impact on wind extremes compared to central tendency (Pryor et al. 2012c).

An understanding of the spatial differences in the performance of downscaled projections, such as the dynamically-downscaled NARCCAP simulations, is critical when interpreting projected future changes. A recently completed comparison for the Great Lakes region of the NCEP-driven simulations for five of the RCMs in the NARCCAP suite to 32-km resolution temperature and precipitation values from the North American Reanalysis (NARR; Messinger 2006) for 1981-2000 indicates large inter-model differences in performance (Figure 5). January mean temperatures from the HRM3 simulation are considerably warmer than NARR temperatures across the entire Great Lakes domain, whereas for the other RCMs the January mean temperatures are warmer than NARR only in the southwestern and/or western portion of the domain. In contrast, the simulated July mean temperatures are cooler than the NARR values across much of the domain for the ECP2, MM5I and WRFG simulations. The CCRM and NARR July mean temperatures are comparable across most of the U.S. portion of the Great Lake region, whereas the HRCM3 mean July temperatures are warmer than NARR in the western portion of the domain. For both months, large deviations in air temperature are seen over the Great Lakes. These differences likely reflect error in both the RCM and NARR temperature fields. In January, the RCMs, particularly ECP2, tend to overestimate mean daily precipitation compared to NARR in the northern portion of the Great Lakes region, whereas in July precipitation is underestimated in the southwestern and/or western portions of the domain (Figure 6).

A final example of the evaluation of NARCCAP simulations for the Midwest focuses on the differences in the distribution of daily maximum and minimum temperatures between the observations at individual stations along the eastern shore of Lake Michigan and the NCEP-driven RCM-simulated temperature at the nearest land gridpoint. Additionally, GCM-driven RCM simulations for a historical period are compared to observed values and the simulated values from the NCEP-driven run. For brevity, histograms are shown for only one location (Eau Claire, Michigan) and one RCM (WRFG). When the annual distribution of daily maximum and minimum temperature is considered (top two histograms in Figure 7), the frequency distribution obtained from the NCEP-driven WRFG simulation follows closely the observed distribution. However, when the observed distributions are compared to the frequency distributions for the historical simulations driven by the GCMs, larger deviations are observed, particularly a substantial cold bias for the CCSM-driven simulation. Comparison by season suggests that this cold bias is particularly large during the winter season. These comparisons indicate that, at least for some applications, the daily maximum and minimum temperature simulations will need to be bias corrected.

January



July

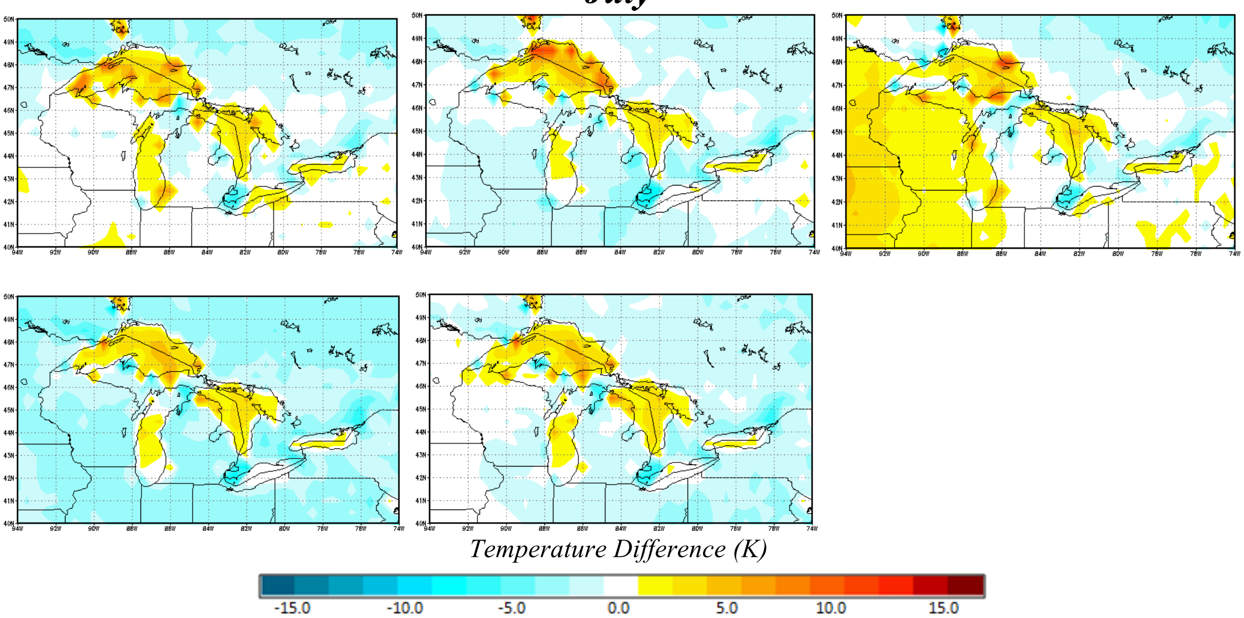


Figure 5. Mean surface-air temperature differences between (a) CRCM, (b) ECP2, (c) HRM3, (d) MM5I, (e) WRFG, and NARR for January (top) and July (bottom). Please note the differences in the scales for the two months. SOURCE: Cinderich (2012) [Permission needed]

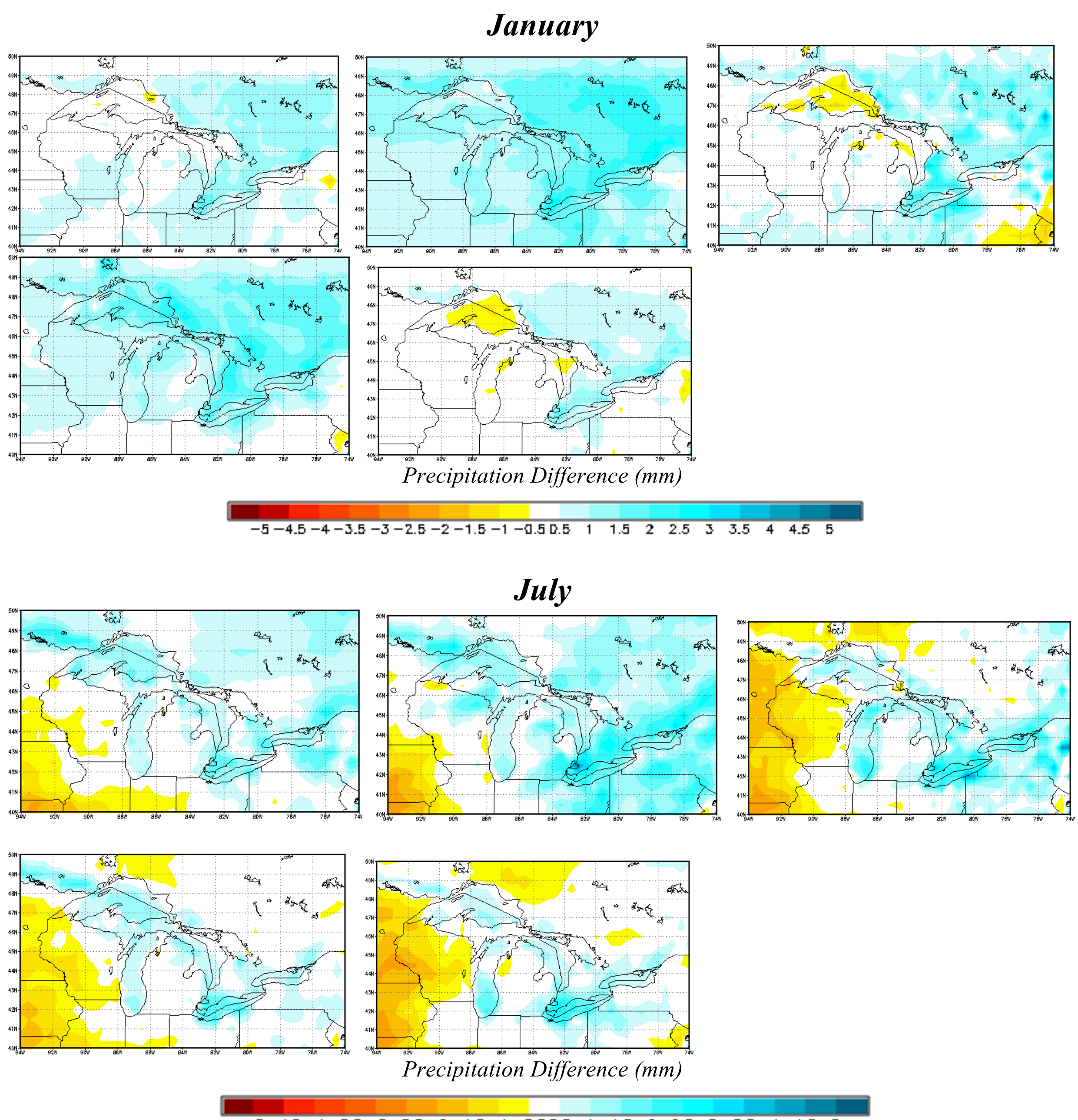


Figure 6. Differences in mean daily precipitation between (a) CRCM, (b) ECP2, (c) HRM3, (d) MM5I, and (e) WRFG, and NARR for January (top) and July (bottom). SOURCE: Cinderich (2012) *[Permission needed]*

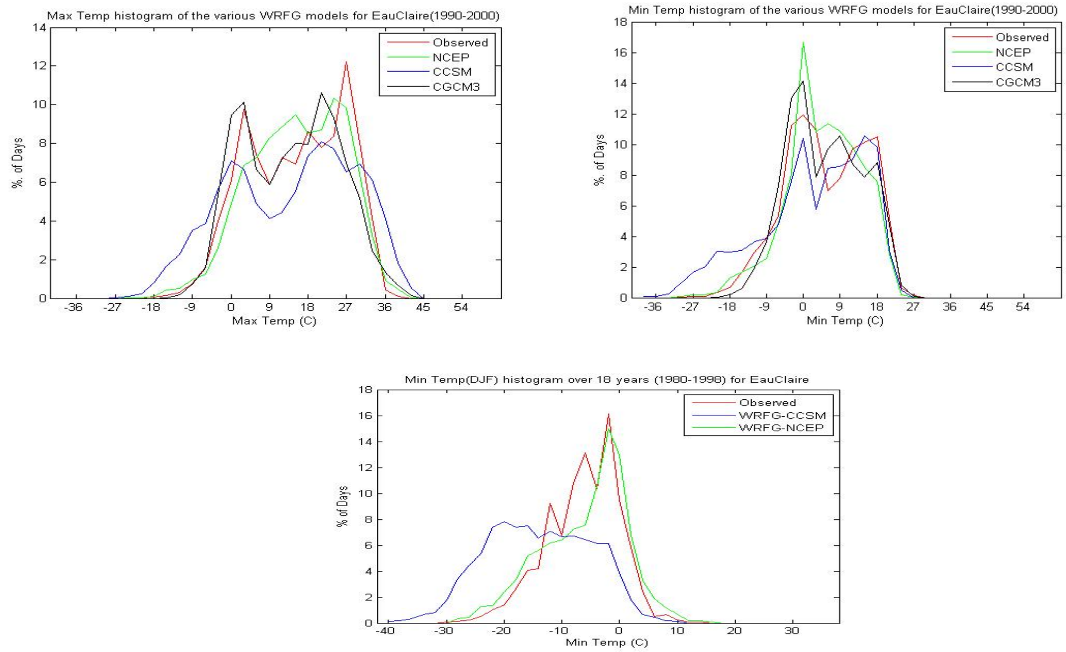


Figure 7: Top row: histograms of the annual distribution of daily maximum and minimum temperature for 1980-2000 a) observed at Eau Claire Michigan (red line), b) simulated by the WRFG, driven by NCEP reanalysis (green line), c) simulated by WRFG driven by the CCSM GCM (blue line), and d) simulated by WRFG driven by the CGCM3 GCM (black line). Bottom row: Observed and simulated values of minimum temperature for winter (December, January, February). SOURCE: Z. Abraham, P.-T. Tan, Perdinan, and J. Winkler (manuscript in preparation).

Projected Future Climate Change for the Midwest Region

The discussion below describes potential future change for three primary surface climate variables, namely precipitation, temperature and wind. For each variable, we attempt to summarize and integrate the numerous climate projections available for the Midwest region, highlighting the consistency, when present, and the uncertainty surrounding the projections. As already noted, available climate projections were developed from a range of GCMs and utilizing a wide variety of downscaling methods.

Precipitation

The majority of previous research on future precipitation change in the Midwest has focused on projected changes in annual and seasonal precipitation totals and on precipitation intensity.

Annual and seasonal precipitation

The large degree of uncertainty surrounding precipitation projections for the Midwest region has been evident since the initial United States National Climate Assessment completed in 2000 which employed simulations from only two IPCC Second Assessment era GCMs (i.e.,CGCM1 and HadCM2). Whereas the CGCM1 scenario suggested much drier future conditions in the northwestern portion of the Midwest and annual increases of 20-40% elsewhere by the end of the century, the HadCM2 scenario projected increases in annual precipitation ranging from 20 to 70 percent across the Midwest by 2100 (Sousounis and Albercock 2000). Similar large differences in annual precipitation by the end of the 21st century were found for Michigan and surrounding states based on the empirically-dynamically downscaled climate projections developed for the Pileus Project from four IPCC Third Assessment era

GCMs (CGCM2, HadCM3, ECHAM4, CCSM), However, in contrast to the earlier findings, almost all the downscaled climate scenarios suggested drier conditions during summer (Andresen et al. 2007).

In support of the IPCC Fourth Assessment, 21 GCMs were utilized to simulate future conditions for 2080-2099 under the SRES A1B greenhouse gas emissions scenario (Christensen et al. 2007). The ensemble mean suggests an increase in annual and winter (December, January February) precipitation for most of the Midwest region but little change or even a small decrease in summer (June, July, August) precipitation (Figure 8). The number of GCMs projecting an increase versus decrease in precipitation provides one measure of the ensemble spread. For the Lower Peninsula of Michigan and northern Ohio, Indiana, and Illinois, over 90 percent of the 21 GCMs projected an increase in annual and wintertime precipitation by 2080-2099, and at least 67 percent of the models suggest increased precipitation elsewhere in the Midwest region. In contrast, approximately half of the 21 GCMs projected an increase in summer precipitation in the Midwest by the end of the 21st century, with the other half suggesting a decrease or little change, again pointing out that a near-zero ensemble mean does not necessarily reflect a consensus of no change. Using the same set of GCMs, Hayhoe et al. (2010) calculated region-wide estimates of precipitation change for the U.S. Great Lakes region under three different greenhouse gas emissions scenarios (A1FI, A2, B1). Projected changes in annual precipitation ranged from -2 to +10 percent for the mid 21st century, and by the end of the century only two of the 21 models projected a decrease in annual precipitation with the remaining models suggesting higher annual precipitation for the U.S. Great Lakes region.

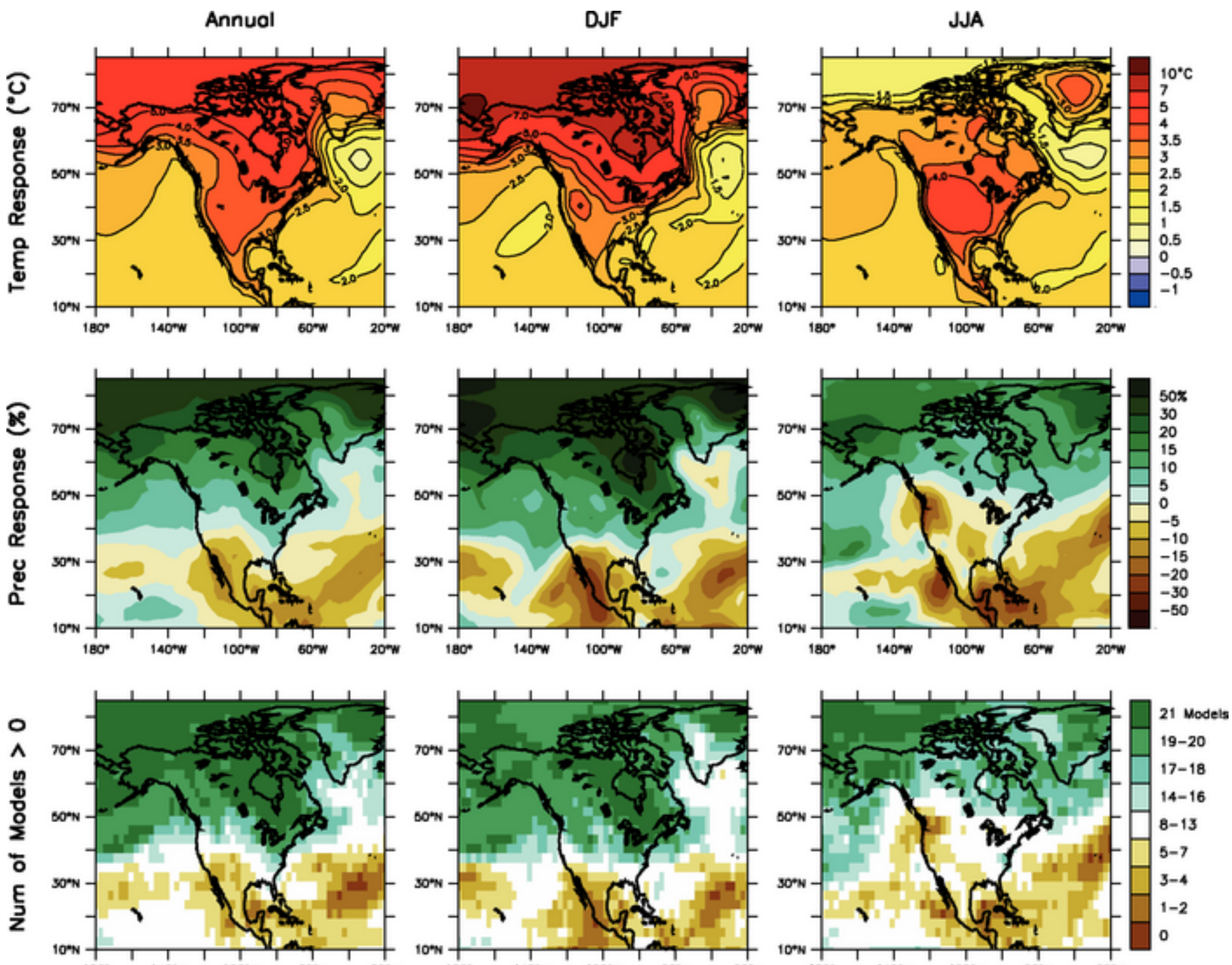


Figure 8. Temperature and precipitation changes over North America from the MMD-A1B simulations. Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models.

Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation. SOURCE: IPCC AR4 Working Group I. [Permission: Permission is not needed if use figure caption exactly as in IPCC report and acknowledge source.]

As expected, the uncertainty surrounding the precipitation projections from the IPCC Fourth Assessment era GCMs is also evident for the downscaled projections developed from these GCMs. One example is the WICCI precipitation projections for Wisconsin that were downscaled from 14 GCMs from the CMIP3 archive (A1B emissions scenario) using a disaggregation method (see Table 2). When displaying the ensemble means on a web resource intended for stakeholder use, the developers limited the displays to those seasons for which the sign of the projected changes was in agreement for the majority of the downscaled projections. Under this criterion, ensemble means are displayed only for the winter (December, January, February) season. At all other times of the year, and for annual accumulated precipitation, the downscaled projections were not in agreement regarding the sign of the projected change. The WICCI projections suggest an average increase in winter precipitation of +3% to +35% across Wisconsin by the mid-21st century. Hayhoe et al. (2010) also found considerable seasonal differences in the sign of the projected precipitation change for the U.S. Great Lakes region based on projections from three GCM simulations from the CMIP3 archive that were downscaled using an disaggregation method to a 1/8 degree resolution. In contrast to the WICCI projections, the scenarios developed by Hayhoe et al. (2010) suggest an increase in regional precipitation in spring as well as winter. For both seasons, larger projected changes were found under higher greenhouse gas emissions, and the projected increases were greatest in the southern portion of the Great Lakes region (i.e., Illinois, Indiana, Ohio).

The projections of precipitation occurrence (the number of wet days) and precipitation intensity (the amount of precipitation on wet days) prepared by Schoof et al. (2010) for a large number of stations across the United States provide some additional insights on future changes in the number of wet days and seasonal and annual precipitation. These projections, developed using disaggregation downscaling applied to simulations from 10 IPCC Fourth Assessment era (CMIP3) GCMs (see Table 2), exhibit a high degree of variability, but results for the Midwest suggest several general tendencies: 1) a decrease in wet day probability during cold season of around -5 percent and -8 percent for 2046-2065 and 2081-2100, respectively; 2) increased cool season (November-March) precipitation by mid and late century for over two-thirds of stations within the Midwest region, with the exception of the northwestern portion where ensemble averages suggested that cool precipitation would decrease; 3) generally a decrease in the number of wet days by the end of the 21st century for summer (June, July, August) but with some inconsistencies between GCMs and stations; and 4) an almost equal number of stations within the Midwest region with projected increases and decreases in warm season precipitation in the 2046-2065 period, with the exception of the southwestern portion of the region where most stations displayed declining warm season precipitation.

The projections of future precipitation change obtained from the coarse-scale output from 15 GCMs from the CMIP3 archive and nine RCM simulations from the NARCCAP archive as described in the climate guidance document prepared for the National Climate Assessment (Kunkel et al. 2012) are generally consistent with the projections described above. The CMIP3 models projected both increases and decreases in precipitation for mid and late-century time periods, as did the NARCCAP dynamically-downscaled projections. The ensemble means of annual precipitation for the nine NARCCAP simulations are largest (10-15% increase) in the Great lakes region, particularly northern Wisconsin and the Upper Peninsula of Michigan, areas where earlier studies (e.g., Christensen et al. 2007) indicate greater consistency in the sign of the projected change. Consistent with the earlier results of Schoof et al. (2010), the ensemble mean changes were smallest (approximately 0 percent) for the southwestern corner of the Midwest region, an area for which GCM projections display considerable uncertainty in the sign of the projected change (Figure 8). A similar but stronger southwest to northeast gradient is seen for the multi-model mean of precipitation change for the 15 CMIP3 models, with average projected changes for the end of the century ranging from an approximately a 5% decrease in the southwestern portion of the Midwest region to close to a 10% increase in the northern portion.

The NCA guidance document also highlights seasonal differences in projected future changes in precipitation. The NARCCAP projections for summer differ from those described above in that a substantial decrease in precipitation is suggested by the ensemble mean in the extreme southwestern portion of the study area. Ensemble mean values are close to zero across the remainder of the Midwest region, very likely reflecting inconsistent signs in the projected summertime precipitation among the nine NARCCAP RCM simulations. The largest projected changes, as indicated by the ensemble means, occur in winter; the multi-model average suggests a precipitation increase of greater than 10 percent over much of the Midwest. The spatial distribution of the NARCCAP multi-model mean change for spring and fall suggests a northwest to southeast gradient with projected changes in fall and spring precipitation of over 10 percent in the northwestern portion of the Midwest and little change (again likely a reflection of inconsistent sign of the projection change) in the eastern and southeastern portions of the Midwest. This spatial pattern had not previously been seen in downscaled projections of spring and fall precipitation change.

Precipitation intensity

Assuming warmer temperatures and consequent higher evaporation, available atmospheric moisture is likely to increase in the future, and one would expect precipitation intensity to increase as well. However, projecting future precipitation intensity is challenging as the probability density function of daily precipitation rates needs to be well simulated in order to have confidence in the projected changes. This is not typically the case (see earlier discussion of evaluation of climate projections). A further complication that is the choice of probability density function for evaluating future changes may influence the interpretation. For example, Gutowski et al. (2007) note that while a gamma distribution can provide a useful general description of precipitation intensity and its change under future climates, other approaches may be more appropriate when considering precipitation extremes. Nevertheless, a small number of analyses have explicitly attempted to evaluate how precipitation intensity may change in the Midwest.

The aforementioned WICCI scenarios suggest that two to three additional heavy precipitation events, defined as daily precipitation rate of two or more inches, can be expected per decade in Wisconsin by the mid-21st century. This would correspond to a 25 percent increase in the frequency of heavy precipitation. Kunkel et al. (2012) reported that the multi-model mean change in the number of days with precipitation greater than one inch from the nine NARCCAP simulations varies from little or no change in the southeastern and eastern portion of the Midwest region to over 30% in the northern portion of the region by mid century. The percentage increases in frequency are projected to be larger for more extreme precipitation events (e.g., precipitation rates greater than one inch, two inches, three inches, four inches). More generally, Schoof et al. (2010) found, based on downscaled climate projections from ten GCMs, that intense precipitation events in the Midwest are likely to either continue at their current frequency or increase in frequency, regardless of the sign of the change in total precipitation. Furthermore, the magnitude of the 90th percentile precipitation rate is projected to increase by mid and late century. They interpreted this finding as indicative of a positive shift in the central tendency and widening of the probability distribution for wet day precipitation intensities. The projected increase in frequency of heavy precipitation is broadly consistent with observed trends in the late 20th century as described by Groisman et al. (2012). They suggest that both global climate change and intensification of agricultural land use may have influenced this trend, and recommend experiments using regional climate models to quantify the relative roles of these influences.

Temperature

Below we highlight projected changes in annual and seasonal mean temperatures, commonly employed temperature indices (e.g., growing degree days), and temperature thresholds and extremes.

Annual and seasonal temperature

Although climate projections are in general agreement that annual and seasonal temperatures will increase by mid century and later, the degree of warming can differ substantially. Starting with the ensemble means from the 21 GCM simulations reported in the IPCC Fourth Assessment (Christensen et al. 2007), annual mean temperatures over the Midwest are expected in increase by approximately 5.5°F (3°C) by 2080-2099 under the A1B emissions scenario (Figure 8). The ensemble means suggest a larger increase in summer (June, July, August), ranging from approximately 8°F (4.5°C) over the western portion of the Midwest and 7°F (4.0°) over the eastern, and in winter (December, January, February) a generally southwest to northeast gradient is observed with a mean increase of more than 6°F (approximately3.5°C) in the southwestern portion of the Midwest and over 9°F (5°C) in the northeast. Based the direct (not downscaled) analysis of the output from 21 CMIP3 GCMS, Hayhoe et al. (2010) report an average increase in mean annual temperature by mid century of approximately 3.5°F (2°C) under lower emissions and approximately 5.5°F (3°C) under high emissions, and an increase by the end of the century of 5.5°F (3°C) under lower greenhouse emissions and 9°F (5°C) under higher emission. Kunkel et al. (2012) employed the same suite of 21 CMIP3 models, and found multi-model mean projected changes in annual mean temperature by the end of the 21st century ranging from approximately 9.5°F in northwestern portion of the Midwest region to 7.5°F in the southeastern portion for the A2 emissions scenario by the end of the century. A distinct northwest to southeast gradient in the multi-model mean projections of the change in annual mean temperature is also observed under the B1 emissions scenario and for a mid century time slice.

Downscaled climate projections in general project somewhat higher changes in annual and seasonal mean temperature than the global model output. The WICCI climate scenarios, downscaled from IPCC AR4 era GCM simulations under the A1B emissions scenario and averaged across all ensemble members, suggest increases in annual mean temperature of 4-9°F in Wisconsin by the middle of the century. The WICCI scenarios also project the largest warming to occur in northern Wisconsin and the least warming along Lake Michigan. Seasonal differences in the rate of warming are also seen from this set of climate projections. Projected warming is least in summer (3-8°F with larger changes projected for northern Wisconsin), whereas the winter mean temperatures are projected to warm 5-11°F by mid 21st century with the largest increases found in northwestern Wisconsin. Spring and autumn mean temperatures in Wisconsin are projected to increase at mid century by 3-9°F and 4-10°F, respectively, with the largest increases in northern Wisconsin.

Compared to the WICCI projections, the downscaled projections developed by Hayhoe et al. (2010) for the U.S. Great Lakes region from three CMIP3 models suggest greater complexity in the seasonal variations in projected changes. For an early period defined as 2010-2039, Hayhoe et al. report larger projected changes in winter compared to spring and summer, but by mid century they found that the seasonality reversed with larger changes projected in summer compared to winter and spring. In terms of spatial variation, the Hayhoe et al. downscaled scenarios suggest larger increases in summer mean temperature in the southern portion of the region (e.g., Indiana, Illinois), whereas projected changes in mean winter temperature are largest in the northern portion (e.g., Wisconsin and Minnesota). Kunkel et al. (2012) found a similar spatial pattern in the distribution of projected temperature change by mid century in winter versus summer from the NARCCAP dynamically-downscaled projections for the Midwest. Additionally, the NARCCAP projections suggest relatively uniform projected changes in spring and autumn mean temperature across the Midwest by mid century.

Temperature thresholds and indices

Although the terms are sometimes used interchangeably, we make a distinction between a temperature "threshold" and a temperature "extreme". A temperature threshold refers to the exceedance of a specified temperature value, selected for its relevance to a natural or human activity or process. In contrast, a temperature extreme is defined in reference of the frequency distribution of temperature and refers to the magnitude of the temperature values at specified probability levels (e.g., the 95th percentile). We confine the discussion below to temperature thresholds, as they have been the focus of most analyses of climate projections for the Midwest. We also discuss in this subsection commonly-used temperature indices, such degree days which are a measure of heat accumulation from a specified base value.

Not surprisingly, the frequency of freezing (≤32°F) temperatures is expected to decrease in the future. The Pileus Project projections for 15 locations in Michigan and surrounding states, when averaged across all ensemble members, suggest that by mid century approximately 15 fewer days will experience minimum temperatures below freezing, whereas by the end of the century a decrease of more than 30 days is projected (see Climate Scenario Tool at http://www.pileus.msu.edu/tools/t_future.htm). Ensemble means for the NARCCAP simulations, when averaged over the entire Midwest region, suggest that by mid century 22 fewer days per year will report minimum temperatures below ≤32°F (Kunkel et al. 2012), although spatial and inter-model variations are apparent.

Changes in the frequency of heat waves are of particular concern due to potential impacts on human health and mortality. The Pileus Project scenarios suggest for Michigan and surrounding areas that the number of days with temperatures ≥95°F, averaged across the ensemble members, will increase by 5 days by mid century and 19 days by the end of the 21st century. For the neighboring state of Wisconsin, the WICCI scenarios project an average increase by mid century in the frequency of maximum temperatures greater than 90°F from approximately 26 days in the southern portion the state to 12 days in the northern portion (see web slide show of projected changes available at http://www.wicci.wisc.edu/climate-change.php). Multi-model means from the NARCCAP simulation suite point to considerable spatial variability across the Midwest region, with an approximately 25 day average increase in the frequency of maximum temperatures ≥95°F in the southern portion of the Midwest region and fewer than 5 days in the northern portion by mid century (Kunkel et al. 2012). The NARCCAP projection (5 days) for the northern Midwest is in good agreement with the mean projected value from the Pileus Project scenarios for the mid century time frame. Additional analysis of the NARCCAP simulations points to a potential increase in the length of heat waves in some parts of the Midwest. The multi-model means suggest that the annual maximum number of consecutive days per year with maximum temperature ≥95°F will increase by 15 days in the extreme southern portion of the Midwest region, although little change is expected across a broad swath of the northern Midwest. The downscaled scenarios developed by Hayhoe et al. (2010a,b) from three GCM simulations also suggest an increased risk of extreme heat waves. By the end of the century, the frequency of heat waves similar to the 1995 heat wave event responsible for nearly 800 deaths in Chicago (Kunkel et al.1996) is projected to range from every other year (low greenhouse gas emissions) to three times per year (high greenhouse gas emissions). Furthermore, heat waves similar to the devastating European heat wave of 2003 could occur in the Chicago metropolitan area, with at least one such event projected before mid century and 5 to 25 events projected to occur by the end of the century, depending on the greenhouse gas emissions (Hayhoe et al. 2010b).

In terms of temperature indices, the ensemble mean of the Pileus Project scenarios suggests that the median date of last spring freeze in Michigan could occur approximately a week earlier than present by mid century and two weeks earlier by late century, with similar changes, although toward a later date, in the median time of occurrence of first fall freeze. These changes in freeze dates should lead to an increase in the length of the frost-free season. The multi-model means of the NARCCAP simulations suggest a fairly uniform increase across the Midwest of approximately 20-25 days in the length of the frost-free season by midcentury (Kunkel et al. 2012). The projected changes based on the Pileus Project scenarios are somewhat smaller with an increase of approximately 15 days projected for mid century and 29 days for late century, although substantial differences are evident between the ensemble members.

Warmer temperatures can be expected to reduce heating requirements but increase cooling requirements, and the climate projections available for the Midwest region support this interpretation. The NARCCAP multi-model means, when averaged across the region, suggest a 15% decrease in heating degree days (Kunkel et al. 2012). When viewed spatially, the greater reductions are seen in the northern portion of the region although the north-south gradient is relatively weak. The magnitudes of the projected changes in cooling degree days are anticipated to be larger than the absolute changes in heating degree days. The NARCCAP multi-model means suggest a 66% increase in cooling degree days, when averaged across the Midwest region. However, a strong south to north gradient is projected with considerably larger increases in cooling degree days in the southern portion of the region. The Pileus Project scenarios suggest a somewhat smaller increase of cooling degree days compared to the NARCCAP simulations. The ensemble mean for the Pileus Project scenarios is approximately 200 cooling degree days in the Lower Peninsula of Michigan compared to 400 CDDs in the same region projected by the NARCCAP simulations.

Finally, growing degree day (GDD) accumulations in the Midwest are projected to increase. The areally-averaged NARCCAP multi-model means suggest a 32% increase in base 50°F GDDs by mid century, whereas the Pileus Project scenarios project an average increase for Michigan of 14% for base 41°F GDDs and 19% for base 50°F GDDs in Michigan by mid century. Larger average increases of 33% and 45% are anticipated in Michigan for base 41°F GDDs and base 50°F GDDs, respectively, by the end of the century.

Freeze Risk

One cannot assume that warmer temperatures will bring more favorable conditions for plants such as perennials that currently are vulnerable to springtime freeze damage. Early spring warm-ups may result in greater freeze risk if plants are at a more advanced stage of development at the time of last spring freeze. On the other hand, if the date of last spring freeze advances to a much earlier date in synchrony with plant development, spring freeze risk may not change or even decrease. Considerable uncertainty exists regarding the future susceptibility of perennial plants in the Midwest to below freezing temperatures when preceding crop development is considered. Winkler et al. (2012), using a suite of climate projections for 15 locations in Michigan and surrounding states that were developed by applying several empirical-dynamic downscaling methods to four IPCC Third Assessment era GCMs, found that approximately half of the scenarios project for the mid and late century little change in growing degree day accumulation (a measure of plant development) at the time of last spring freeze whereas the other half project greater crop development at the time of freezing temperatures. Similarly, an approximately equal number of scenarios suggested an increase versus a decrease in the median GDD accumulation outside the frost free period (i.e., the growing season).

Apparent temperature

In the Midwest, high summer temperatures are often accompanied by elevated near-surface humidity, which enhances human heat stress through reduction of evaporative cooling from the skin (ref). The combined effect of temperature and humidity on human heat stress is often quantified using 'apparent temperature'. While historical tendencies in air temperature over the Midwest have been of comparatively modest magnitude, apparent temperatures have exhibited marked increases (ref), driven in large part of increases in atmospheric moisture (Rogers et al. 2009). Projections for future apparent temperature regimes across the Midwest derived using disaggregation downscaling of 10 GCMs under three greenhouse gas emissions scenarios all suggest an increase in the magnitude of apparent temperature, with a substantial fraction of the increase deriving from increased humidity. Thus the probability of heat stress events is projected to increase across the Midwest in the coming decades relative to the historical period (Schoof 2012).

Wind

Recent analyses of RCM output from the NARCCAP suite has focused on possible climate change signals across a range of wind climate descriptors including the mean, 50th percentile, 90th percentile, 95th percentile, 20 and 50 year return period wind speeds and wind energy density (i.e., wind resource) (Pryor & Barthelmie 2011, Pryor et al. 2012b). Some of these analyses assessed whether there was consistency in the change of the different parameters in the middle of the current century versus the end of the twentieth century. The results generally display only a weak consistency on the climate change signal in any of the descriptors. However, approximately 22% of grid cells show a lower 90th percentile wind speed in all of the RCM simulations. In keeping with results of analyses that indicate the RCMs generally develop extreme wind climates that are to some degree independent of the lateral boundary conditions, extreme wind speeds are generally not characterized by a consistent change on the basis of the eight sets of simulations considered. Only 1% of grid cells over the contiguous USA indicate a consistent signal of either higher or lower values for the 20- or 50-year return period wind speed in the future. Changes in 50-year return period wind speeds over the Midwest from four of the NARCCAP simulations are shown in Figure 9. As for the entire NARCCAP domain, relatively few grid cells within any of the GCM-RCM combinations exhibit substantially higher or lower values for the extreme wind speed in the future. However, it is important to note that the wind climate exhibits large inherent variability at a range of time scales from minutes to decades. Analyses of a single future period of only 22 years duration precludes general inferences regarding trends in any aspect of the wind climate. Earlier research over Europe has shown that in the near-term, inter-annual and inter-decadal variability dominates over any temporal trend and that, based on results of dynamical downscaling, intense and extreme winds are unlikely to evolve out of the historical envelope of variability until the end of the current century (Pryor et al. 2012a).

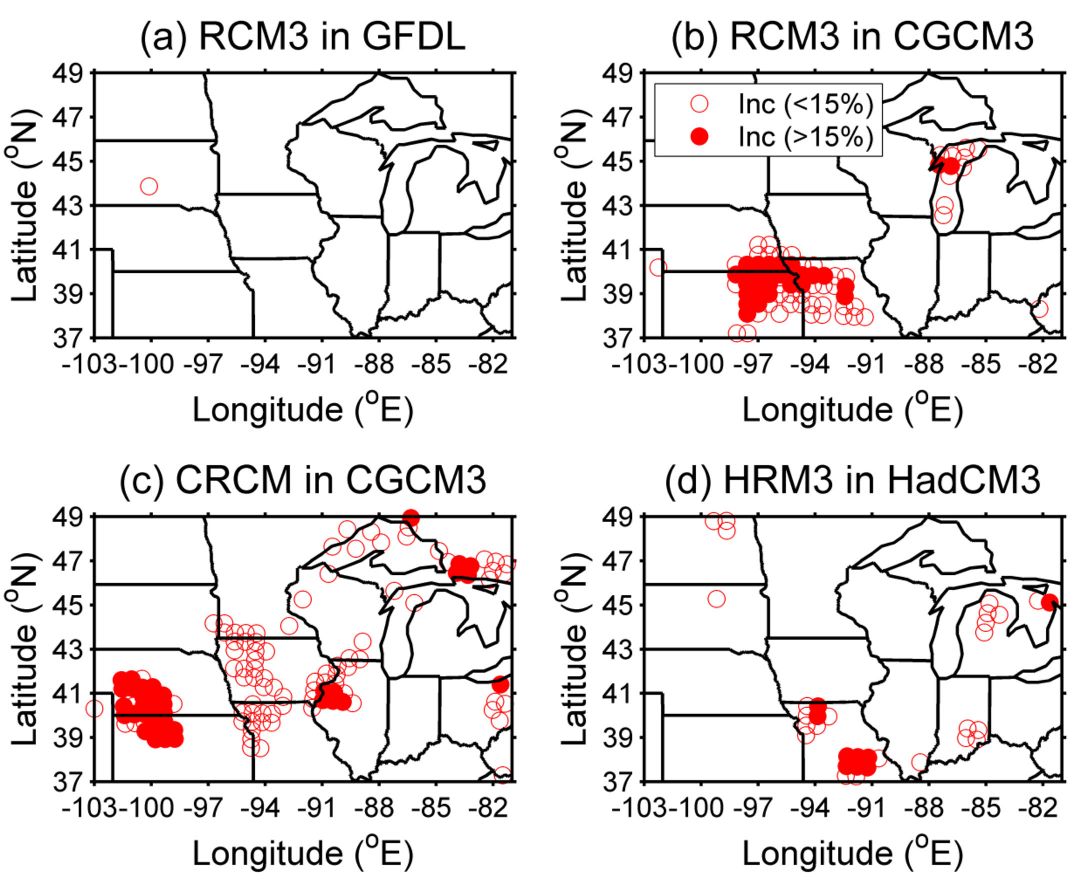


Figure 9: Difference in the fifty-year return period sustained wind speed (U_{50yr}) over the Midwestern US for 2041-2062 vs. 1979-2000. The frames show the different AOGCM-RCM combinations. The magnitude of change is only shown for grid cells where the value for the future period lies beyond the 95% confidence intervals on the control period. Note; none of the grid cells behind the legend in frame (b) exhibited significant changes. SOURCE: Pryor and Barthelmie (2012b). *Permission needed.*

Level of Confidence

We are in agreement that the following statements reflect the level of confidence that can be placed on future climate projections for the Midwest region:

- There is no single best climate model or downscaling approach.
- There is greater confidence in projected temperature change than precipitation change.
- In spite of confidence in future warmer temperatures, change in freeze risk remains uncertain.
- The degree of uncertainty surrounding precipitation change remains high.
- There is little confidence in the sign (positive or negative) of change in mean precipitation for the warm season. There is somewhat greater confidence in projections of increases in the frequency and intensity of extreme warm season precipitation events.
- The use of a multimodel mean of a projected change may be misleading, particularly for projected changes in precipitation.

Concluding Remarks

In this whitepaper we introduced readers to key considerations when using and interpreting climate projections. Furthermore, we attempted to integrate multiple climate projections for the Midwest region, with the stated goal of identifying consistencies across projections and also uncertainty surrounding projected future changes. This evaluation led to a number of statements of confidence in future projections, that highlight greater uncertainty surrounding future projections of precipitation compared to other climate variables.

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Table 1: Available climate change projections for the NCA Midwest region.

Name/ Reference	Coverage/Resolution / Variables/Period	Ensemble Size	Downscaling Procedures	Considerations when using or interpreting	Availability
CMIP3 GCM archive (Meehl et al. 2007)	• Global • Spatial resolution varies by GCM • archived at monthly time step, but finer time steps available for most models	• over 20 GCMs (AR4 era) • 3 emissions scenarios (SRES A2, A1B, B1)	Not downscaled	• Spatially and temporally coherent • Climate variables are physically consistent	• Graphical summaries available in IPCC AR4 Working Group I report. • Time series of monthly precipitation and mean temperature available from the Program for Climate Model Diagnosis and Interpretation (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php)
Bias Corrected and Downscaled WCRP CMIP3 Climate Projections (Maurer et al. 2007)	• Global • 1/8^{o} lat/long resolution • Mid century and late century time slices	• 16 GCMs (IPCC AR4 era) • 3 emissions scenarios (SRES A2, A1B, B1)	Disaggregation (BCSD) method. Gridded temperature and precipitations observations were upcsaled to a 2° resolution and GCM projections were regridded to this resolution. Quantile mapping was used calculate change factors which were then downscaled using		Monthly time series available through Climate Wizard http://www.climatewizard.org). and at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections

			a simple inverse distance approach and applied to the original finely gridded observed dataset.		
TYN SC 2.0 (Mitchell et al. 2004)	• Global • 0.5^{o} lat x0.5^{o} long • Mean monthly cloud cover, DTR, precipitation, temperature, vapor pressure • 2001-2100	• 5 GCMs (IPCC TAR era). • 4 emission scenarios (SRES A1FI, A2, B2, B1)	Disaggregation downscaling. Spatial interpolation using thin plate spline scheme.		Available at http://www.cru.uea.ac.uk/cru/data/hrg/
WorldCLIM	• Global coverage • ~1km resolution • Climatological (30 year) mean monthly temperature and precipitation • 7 overlapping 30-year periods in 21st century	• 3 GCMs (IPCC TAR era) • 2 SRES emissions scenarios	Disaggregation downscaling (spatial interpolation)	• Spatially coherent	Available at http://worldclim.org
International Centre for Tropical Agriculture (CIAT)	• Global • 4 spatial resolutions (30 arc-seconds, 2.5 arc-minutes, 5 arc-minutes and 10 arc-minutes). • Climatological (30 year) mean monthly temperature and precipitation	• IPCC AR4 models	Disaggregation downscaling (spatial interpolation)	• Spatially coherent • Physically consistent	Available at http://gisweb.ciat.cgiar.org/GCMPage/

10’ Future Climate Grids (Tabor and Williams 2010)	• Global • 10′ resolution • Climatological (20 year) mean monthly temperature and precipitation • Two time slices, 2041–2060 and 2081–210	• 24 GCMs (IPCC AR4 era) • 3 emissions scenarios (SRES A1b, A2, B1)	Disaggregation downscaling. GCM simulations are debiased respect to their mean differences from 20th-century observations. The differences are downscaled to 10′ resolution with a spline interpolation and then added to mean 20th century climatologies from the CRU CL2.0 dataset.	• Spatially coherent • Physically consistent	Available at http://ccr.aos.wisc.edu/resources/data_scripts/ipcc/index.html
NARCCAP (Mearns et al. 2012)	• North America • ~50 km • 3-hourly time step • Multiple climate variables including temperature, precipitation, humidity and wind • Two time slices, 1960-1990 and 2040-2070	• 9 simulations developed from combinations of 4 GCMs (IPCC AR4 era) 6 RCMs • SRES A2 emissions scenario	Dynamic downscaling (RCM models)	• Physically consistent climate variables • Spatially and temporally coherent • GCM-driven simulations likely need bias corrections or further downscaling	http://www.narccap.ucar.edu/
Pileus Project (Winkler et al., 2012)	• 15 locations in the Great Lakes region of North America ; • Daily temperature	• 4 GCMs (IPCC AR4 era) • 2 emissions scenarios (A2,	Empirical-dynamic downscaling. Regressions	• Although transfer functions developed	User tool available to view summary graphics for temperature scenarios available at

	and precipitation • 2000-2099	B2) • 8 empirical-dynamic downscaling variants based on "perfect prog" approach	equations were developed for each location that related large-scale circulation (the predictors) to surface climate variables (the predictands).	separately for each variable and location, use of set of spatially and temporally coherent predictor variables imparts some spatial and temporal coherency to the predictands.	www.pileus.msu.edu Precipitation scenarios available from author
WICCI Notaro et al. 2011	• Wisconsin • 0.1° lat x 0.1° lon • Daily temperature and precipitation • 1980-2055	• 14 GCMs from CMIP3 archive • SRES A1B emissions scenario	Disaggregation downscaling. Statistical relationships were developed between GCM fields and parameters of the probability density function for a local climate variable Statistical. The parameters were interpolated to fine grid, and a random number generator was used to obtain daily values.	• Daily values are not spatially coherent.	Maps of multi-model means available at http://www.wicci.wisc.edu/
Hayhoe et al 2010	• US Great Lakes region • 1/8 degree grid and individual weather	• 3 GCMs from CMIP3 archive • SRES A1FI, B1 emissions	Disaggregation downscaling using 1) the Maurer et al.	• Daily values are not spatially or temporally coherent	Contact author. [NOTE: an updated dataset for the entire US will soon be released and available via

	stations • Monthly and daily temperature and precipitation	scenarios	2007 approach to downscale monthly temperature and precipitation to a regular grid, and 2) asynchronous quantile regression for downscaling to individual stations and daily resolution		the USGS climate projection port]
Schoof 2009	• 53 stations in the Midwest • Daily temperature • 3 time slices (1961-2000, 2046-2065, 2081-2100)	• 8 GCMs (IPCC AR4 era) • A2 emissions scenario	Empirical-dynamic downscaling. Transfer functions were developed separately for each location that related large-scale values of mid-tropospheric temperature and humidity to surface temperature (perfect prog method).	• Although transfer functions developed separately for each location, use of spatially and temporally coherent large-scale predictor variables imparts some spatial and temporal coherency to the predictands.	Contact author.
Schoof et al. 2010	• 963 stations in United States • Daily precipitation • 3 time slices (1961-2000, 2046-2065, 2081-2100)	• 10 GCMs (IPCC AR4 era) • A2 emissions scenario	Disaggregation downscaling. Statistical parameters of gamma distribution were	• Daily precipitation values are not spatially coherent	Contact author.

			downscaled using first-order Markov chain.		
Kunkel et al. 2012	• Midwest • Multi-model averages of projected changes in annual and seasonal mean temperature and precipitation and for extremes and thresholds	• NARCCAP RCM simulations • A2 and B1 emissions scenarios for CMIP3 models; A2 emissions scenario for NARCCAP simulations	Dynamic downscaling	• Spatial and temporally coherent	Guidance document prepared for the authors of the NCA report and members of the regional and sectoral technical input teams. Available from NCA.

Agriculture in the Midwest *(Jerry Hatfield)*

Agriculture in the Midwest United States (Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin) represents one of the most intense areas of agriculture in the world. This area is not only critically important for the United States but also for world exports of grain and meat but for the United States economy. In the 2007 Census of Agriculture these states had a market value of crop and livestock products sold of $76,989,749,000 (USDA Census of Agriculture, 2007). Within the U.S., Illinois, Iowa, and Minnesota ranked 2, 3, and 4 in the value of crops sold and Iowa ranked 3rd in the value of livestock, poultry and their products and Wisconsin ranked 7th in the value of livestock, poultry and their products sold. The economic value of agriculture in the Midwest encompasses corn, soybean, livestock, vegetables, fruits, tree nuts, berries, nursery and greenhouse plants. The economic value of the crop and livestock commodities in these states continues to increase because of the rising prices.

Midwestern states are considered to be the Corn Belt; however, there is a diversity of agricultural production beyond corn and soybean. Area in corn for the Midwest in 2007 was 20,360,396 hectares followed by soybean with 14,277,472 hectares. The diversity of agricultural production is shown in Table 1 for the amount of the commodity produced and the state rank based on the 2007 Census of Agriculture (USDA, 2007).

Table 1. Commodities produced and state rank for the Midwest region of the United States.

Commodity	Illinois		Indiana		Iowa		Michigan		Minnesota		Ohio		Wisconsin	
	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank
Livestock (millions of animals)														
Layers	5.3	18	24.2	3	53.8	1	9.0	14	10.6	11	20.1	2	4.9	19
Hogs and pigs	4.3	4	3.7	5	19.3	1	1.0	14	7.6	3	1.8	10		
Pullets	0.9	28	6.9	5	11.4	1	2.0	16	3.2	12	6.8	6	1.2	22
Turkeys	0.8	19	6.0	7	4.0	9	2.0	16	18.3	1	2.0	14	3.7	10
Cattle and calves	1.2	26			3.9	7	1.0	30					3.4	9
Broilers			5.5	23					8.6	21	10.0	20	7.1	22
Milk and other dairy products from cows ($100,000)														
	340.3	20	583.2	14	689.7	12	1,285.6	7	1,475.9	6	861.3	11	4,573.3	2
Crop Production (1000 Hectares)														
Corn for grain	5,300.0	2	2,574.9	5	5,614.1	1	951.3	11	3,157.1	4	1,459.4	8	1,315.6	10
Soybean	3,356.5	2	1,936.0	4	3,485.6	1	694.3	12	2,539.0	3	1,714.4	6	551.6	15
Forage	240.1	32	221.3	33	455.5	23	469.6	21	964.7	15	468.0	22	1,132.1	7
Corn for silage			42.9	17	89.3	8	120.3	7			74.0	11	296.5	1
Oats for grain					27.0	7								
Wheat for grain	360.8	12	146.7	19			211.7	17	691.4	10	296.3	15		
Sorghum for grain	31.0	11												
Sugarbeets for sugar									196.5	1				
Vegetables													120.3	4

Impact of climate on agricultural production in the Midwest varies among years particularly in grain, vegetable, and fruit production. Fortunately, there are extensive records of agricultural production across the Midwest which allows for a detailed examination of the variation among years and the relationship to changes in the weather in each growing season and the changing climate over the Midwest. Variation among the years for corn grain can be seen in the records since 1866 for Iowa and Michigan production (Fig. 1), soybean for Illinois and Indiana (Fig. 2), sweet corn in Minnesota and Wisconsin (Fig. 3), and potato in Michigan and Wisconsin (Fig. 4).

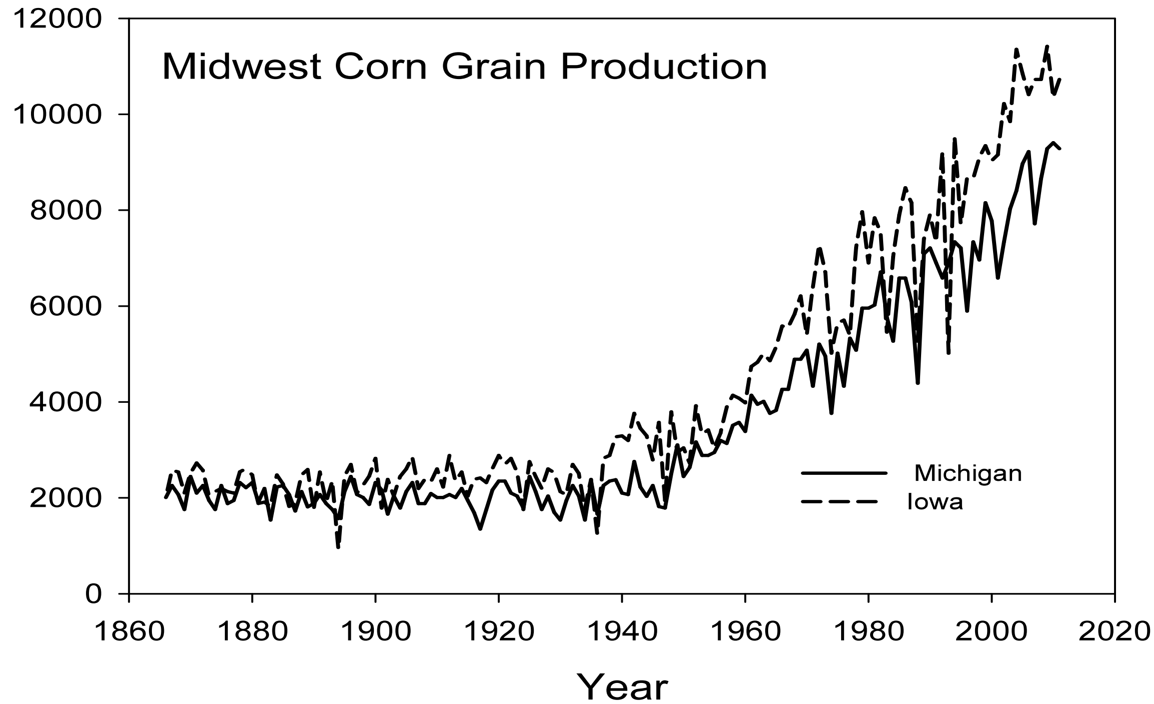

Figure 1. Annual corn grain yields for Iowa and Michigan from 1866 through 2011 (Source: USDA-NASS).

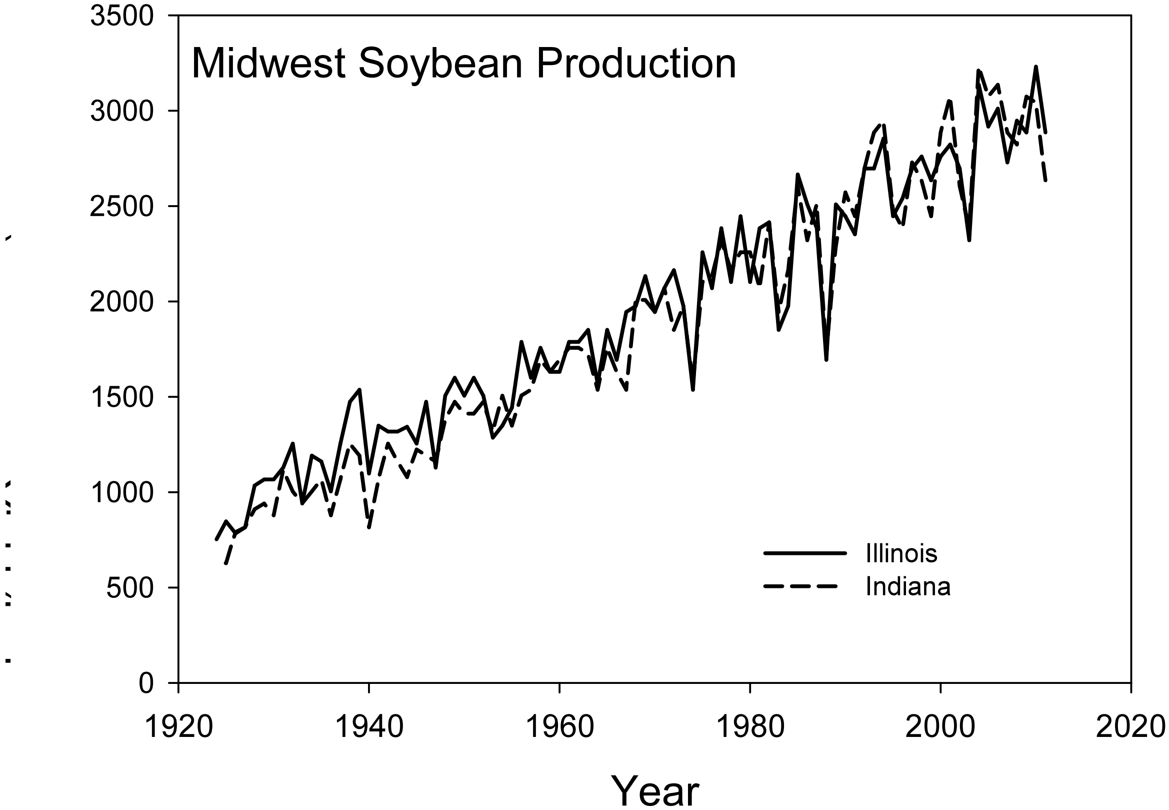

Figure 2. Annual soybean grain yields for Illinois and Indiana from 1924 through 2011 (Source: USDA-NASS)

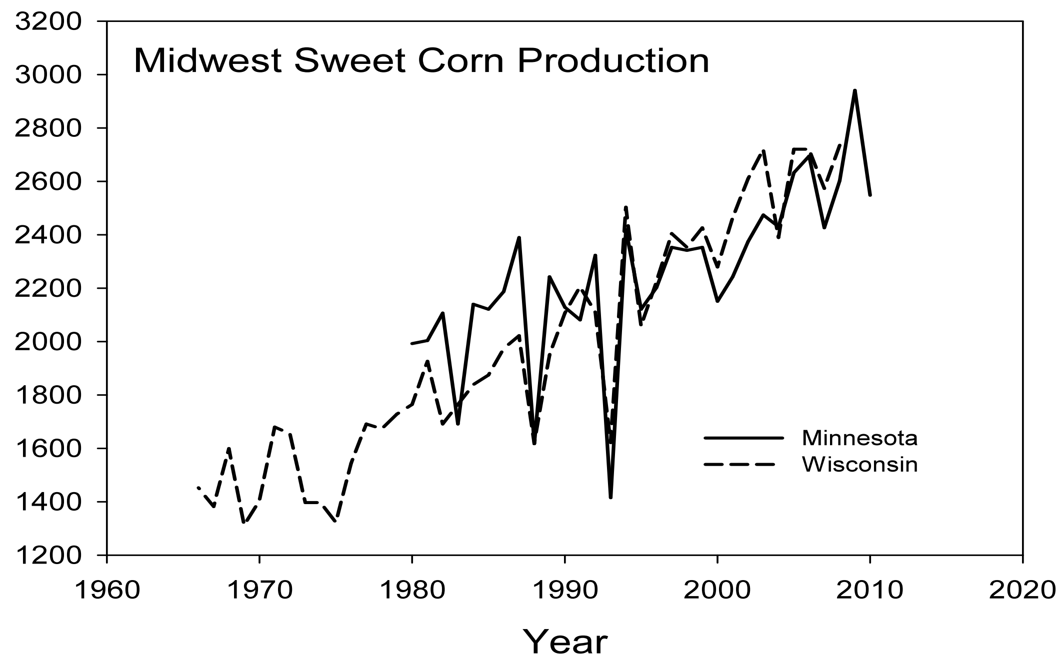

Figure32. Annual sweet corn production from 1968 through 2010 for Minnesota and Wisconsin (Source: USDA-NASS).

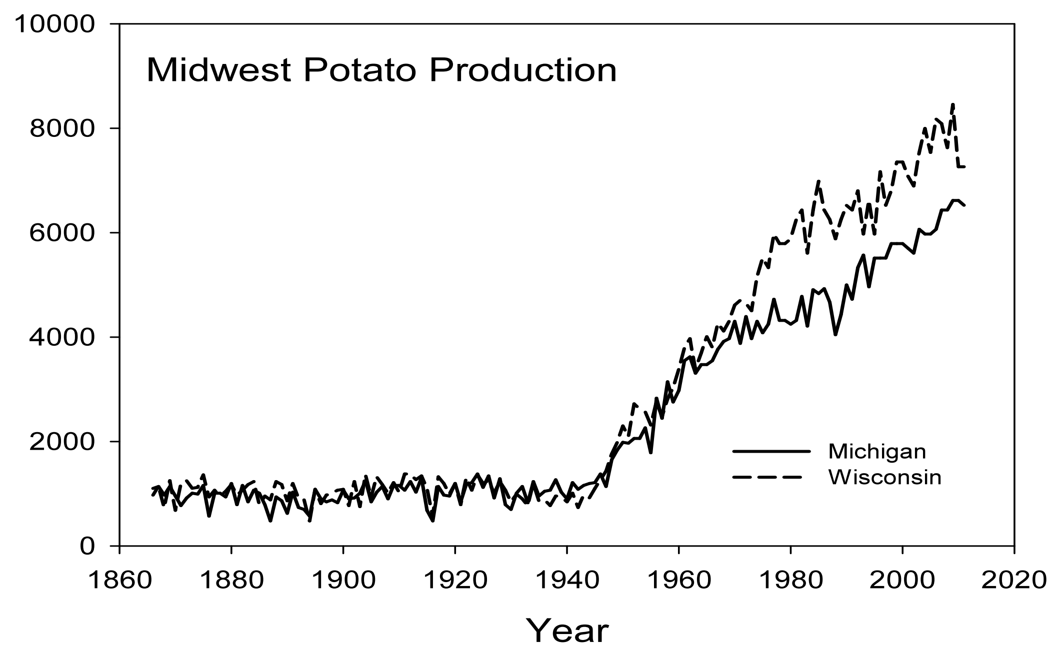

Figure 3. Annual potato production for Michigan and Wisconsin from 1866 through 2011 (Source: USDA-NASS)

Climate impacts on production are detectable throughout the history of observations in the United States. There is another trend which is noteworthy in these observations which is related to the rapid and steady increase in annual production for crops beginning after the mid-1940's with the introduction of commercial fertilizers and enhanced genetic materials. However, the introduction of improved agronomic practices has not alleviated the impact in years with large impacts from unfavorable weather during the growing season. Soybean production has shown a steady increase since records began for the Midwest in 1924 and there are years with large reductions in yield which are related to extremes due to drought (1988) or flooding (1993). In the grain crops, exposure to extremes, e.g., drought in 1988 created a 30% reduction in yield and the floods of 1993 which caused a 44% reduction in yield from the potential sweet corn yield for that year as defined by Hatfield (2010). Water availability is the dominant climatic factor causing yield variation among years. These are significant decreases in crop yield which is observed in all states because of the geographical extent of major climatic events. However, yield decreases in most years average between 15-20% from the potential yield due to short-term exposure to stresses. These stresses can be characterized as periods in which soil water is not available to meet the atmospheric demand or the temperatures are not in the optimal range for growth. It is important to realize that there is only a small fraction of the years in which there is no stress imposed by weather on crop growth or yield.

Temperature effects on plant growth have not been extensively studied and future impacts of climate change may be more related to changes in temperature compared to the other climatic factors. Each of the crops grown in the Midwest has a specific temperature range characterized by a lower and upper limit at which growth ceases and an optimum temperature at which growth proceeds at a rate for maximum size of the plant. These temperature limits have been recently defined for several species relative to climate change by Hatfield et al. (2011). The effects of temperature as a climate change parameter has been recently evaluated by several different groups in which they suggest that temperature stresses may be extremely significant in terms of affecting crop growth and yield. Lobell et al. (2011) observed that the changes in temperature which have already occurred from 1980 to 2008 have reduced crop productivity. They concluded that corn (*Zea mays* L.) yields already declined 3.8% and wheat (*Triticum aestivum* L.) declined 5.5% compared to the yields without climate trends. An important conclusion from this research was the observation that climate trends have been significant enough effect to offset the yield gains from technology and CO_2 increases. Kucharik and Serbin (2008) reported that projected corn and soybean (*Glycine max* (L.) Merr.) yields for Wisconsin would be significantly impacted because of rising temperatures. Analyses such as these and the results reported by Hatfield (2010) reveal that climate has already affected crop production. The recent study by Schlenker and Roberts (2009) discussed the potential nonlinear effects of warming temperatures on crop yields in the United States and showed there would be large impacts on productivity because of plants being exposed to conditions which are outside the thermal boundaries for optimal growth. A challenge for research is to begin the process of quantifying the temperature response of plants.

One of the changes in the climate which has a negative impact on plant growth and yield is the increase in the nighttime temperatures more than the daytime temperatures. The effect of minimum temperatures on plant growth has been observed in the small grains, e.g., wheat and rice (*Oryza sativa* L.) When temperatures increased above 14°C there was a decreased photosynthesis after 14 days of stress causing wheat grain yields to decrease linearly with increasing nighttime temperatures from 14 to 23°C which in turn leads to lower harvest indices (Prasad et al., 2008). In their studies, when nighttime temperatures increased above 20°C there was a decrease in spikelet fertility, grains per spike, and grain size. Temperature effects on pollination and kernel set in corn may be one of the critical responses related to climate change. Pollen viability decreases when plants are exposed to temperatures above 35ºC (Herrero and Johnson, 1980; Schoper et al., 1987; Dupuis and Dumas, 1990). Pollen viability (prior to silk reception) is a function of pollen moisture content and strongly dependent on vapor pressure deficit (Fonseca and Westgate, 2005). Although there is limited data on sensitivity of kernel set in maize to elevated temperature, there is evidence suggesting the thermal environment during endosperm cell division phase (8 to 10 days post-anthesis) is critical (Jones et al., 1984). Temperatures of 35ºC compared to 30ºC during the endosperm division phase reduced subsequent kernel growth rate (potential) and final kernel size, even after the plants were returned to 30ºC (Jones et al., 1984). When corn plants are exposed to temperatures above 30ºC, cell division was affected which reduced the strength of the grain sink and ultimately yield (Commuri and Jones, 2001). Leaf photosynthesis rate has a high temperature optimum of 33 to 38ºC with a reduction in photosynthesis rate when corn plants are above 38ºC (Crafts-Brandner and Salvucci, 2002). In a controlled environment study on sweet corn (*Zea mays* L. var. *rugosa*), Ben-Asher et al. (2008) found the highest photosynthetic rates occurred at temperatures of 25/20 while at 40/35°C (light/dark) photosynthetic rates were 50-60% lower. They concluded from these observations that photosynthetic rate declined for each 1°C increase in temperature above 30°C. The expectation is that corn grain plants would show a similar response. In soybean, there is a temperature effect and a comparison of growth at 38/30 versus 30/22ºC (day/night) temperatures, revealed elevated temperatures reduced pollen production by 34%, pollen germination by 56%, and pollen tube elongation by 33% (Salem et al., 2007). Exposure to air temperatures above 23ºC caused w a progressive reduction in seed size (single seed growth rate) with a reduction in fertility above 30°C leading to a reduced seed harvest index at temperatures above 23ºC (Baker et al., 1989).

The chances for continued impacts for climate change are increasing according to a recent study by Rahmstorf and Coumou (2011) in which they attributed the extreme heat events in Russia during 2010 to climate change and concluded these extremes would not have occurred without climate change. They projected an increase in extremes to occur around the world as a result of climate change. The expectation for a changing climate both in means and extremes will cause impacts on agriculture.

Increases in high temperatures are not the only affect on crops. Although, there has been a warming trend in temperatures there has been no change in the dates for the first or last freeze event in the year. For perennial crops this means plants may begin to grow and produce flower buds in the spring and then be exposed to freezing conditions which would destroy the crop. Fruit and berry crops across the Midwest will be subjected to more extreme conditions and negatively impact growth and production. While there is evidence of changing climate, the overall impacts on perennial crops becomes more uncertain because of the uncertainty in the chilling requirements.

Changes in CO_2, temperature, and precipitation will impact agriculture in the Midwest. Indications are that increasing CO_2 will exert a positive influence on C_3 plants in terms of growth; however, the positive effect on grain yield has not been as large (Hatfield et al., 2011). An analysis by Bernacchi et al. (2007) using soybean grown in a free air carbon dioxide enrichment (FACE) system at 550 compared to 375 $\mu mol\ mol^{-1}$ showed a 9 to 16% decrease in ET with the range of differences over the three years caused by seasonal effects among years. There has been evidence that the reduction in ET caused by increasing CO_2 will diminish with increasing temperatures; however, this has not been evaluated in Midwestern crops.

Changes in climate across the Midwest will be evident in the precipitation timing more than in the amounts. There is evidence of an increase in the spring precipitation across the Midwest and an increase in the intensity of storm events. Climate model projections for precipitation changes don't exhibit the same degree of confidence compared to the observations across the Midwest. The shifts in precipitation will affect field preparation time in the spring. An analysis of workable field days for April through mid-May in Iowa has shown a decrease from 22.65 days in the period from 1976 through 1994 compared to

19.12 days in 1995 through 2010. This is a major change in the days available during the spring for field work. There is an increased risk for both field work and soil erosion because of these shifts in precipitation. There has been little attention directed toward the workable days in the fall during harvest periods and the potential impact on grain, fruit, or berry quality. Impacts of increased precipitation and intense events are associated with increased erosion and water quality impacts (nutrients and pesticides). It is expected that these impacts will increase with increased spring precipitation because of the lack of ground cover with vegetation.

Water quality impacts relative to a changing climate have not been investigated; however, these impacts are related to soil water excesses. Shifts in precipitation patterns to more spring precipitation coupled with more intense storms creates the potential for increased water quality (sediment, nitrate-N, and phosphorus). In an analysis of the Raccoon River watershed in Iowa, Lucey and Goolsby (1993) observed nitrate-N concentrations were related to streamflow in the river. Hatfield et al. (2009) showed that annual variations in nitrate-N loads are related to the annual precipitation amounts because the route of movement into the river was through leaching through subsurface drains as the primary path into the stream and river network. The Midwest is an extensively subsurface drained area and these drains would carry nitrate-N from the fields and across the Midwest with the current cropping patterns which do not have amount of water use during the early spring (Hatfield et al., 2009). Increased intensity of spring precipitation has the potential for increased surface runoff and erosion in the spring across the Midwest. Potential increases in soil erosion with the increases in rainfall intensity show that runoff and sediment movement from agricultural landscapes will increase (Nearing, 2001). Water movement from the landscape will transport sediment and nutrients into nearby water bodies and further increases in erosion events can be expected to diminish water quality.

Indirect impacts from climate change on crop, fruit, vegetable, and berry production will occur because of the climate change impacts on weeds, insects, and diseases. This has not been extensively evaluated across the Midwest and presents a potential risk to production. Significant effects on production may result from weed pressure caused by a positive response of weeds to increasing CO_2 (Ziska, 2000; 2003 a; 2003b; Ziska et al., 1999; Ziska et al., 2005). The effects of CO_2 on increasing weed growth may lead to increased competition in fields without adequate weed management. A void of knowledge is the effect of changing climate on insects and diseases and the extent of a changing risk pattern on agricultural production.

Livestock

Climate stresses on livestock in the Midwest is decreased because most of the species are grown in confined production facilities where there is control of the temperature and humidity and the animals are not exposed to the natural environment. In these systems, there may be a greater effort directed toward energy efficiency in these facilities and management to ensure a limited exposure to extreme conditions during transport of animals to processing facilities. Dairy cattle are often grown in unconfined facilities; however, shelter is provided for these animals from severe weather events. Increases in temperature and humidity occurring and projected to continue to occur under climate change will impose a significant impact on production of the different species shown in Table 1. Exposure of livestock species to the combination of temperature and humidity factors will increase the stress levels; however, these effects have not been extensively quantified across the Midwest. The indirect impacts of climate change on livestock will occur because of the potential for a changing climate to affect the occurrence of insects and diseases. There is an increased risk of the exposure of animals to insect and disease pressure as a result of climate change; however, these relationships have not been established for the animal species of the Midwest.

Adaptation

Agriculture is a very fluid system and within annual crop production there is continual adaptation to adjust to the changing climate conditions. There are shifts in planting dates dictated by the precipitation amounts occur each year. In order for producers to make large shifts in agronomic practices, e.g., maturity dates on crops, there would have to be a consistent pattern in the climate trends and events each year. Adaptation strategies for Midwest crop agriculture will have to include practices which protect the soil from erosion events while at the same time increasing the soil organic matter content through carbon sequestration via improved soil management (Hatfield et al., 2012). Adaptation strategies for livestock across the Midwest would be relatively minor because of the majority of the production systems already occurring under confined spaces with controlled environments.

Crop insurance has been used as a process to offset losses to producers due to weather events during the growing season. Given the uncertainty in the climate change it is difficult to evaluate how crop insurance payments will change in the future (Beach et al., 2010). There have been shifts in the perils which have triggered crop insurance payments for the past 20 years with a shift from drought to flooding and excess water being the major cause of insurance claims.

Risk Assessment

Exposure to extreme events for both temperature and precipitation can cause reductions in plant production and yield. There is evidence in the observed yield history for crops grown in the Midwest that extremes can have significant impacts on production levels; however, there are impacts on yields from variability in weather during the growing season caused by short-term weather impacts, e.g., less than normal rainfall but not enough deficiency to trigger drought. With the likelihood of an increase in the occurrence of extreme events across the Midwest, we could expect a greater variation in production amounts. It is also interesting to note in these records that not all extreme events impact the entire Midwest with some events (flooding or drought) being more localized and affected the production within a state and even isolated to a few counties. Development of a risk assessment for assessment of climate impacts on agriculture will require the application of crop simulation models into which climate scenarios can be incorporated. This approach would allow for an assessment of the potential impacts of climate on future production levels but also allow for the evaluation of the efficacy of various adaptation strategies.

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White paper on impacts & adaptation in the Biodiversity and Ecosystems sector
Input to the National Climate Assessment, Midwest Region chapter

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Five key points:

1) Rapid climate change over the next century will stress a majority of species in our region, and is likely to accelerate the rate of species declines & extinctions (very likely). In the Midwest, key drivers of these stresses and extinctions are likely to be interactions between climate change and current stressors (habitat loss, invasive species, hydrologic modifications), rather than more direct climate impacts (likely).

2) Due to geographic factors (relatively flat topography and moderate to high latitudes), species in the Midwest that respond to increasing temperatures by shifting ranges will need to move particularly fast relative to species in other parts of the continental U.S. to track projected changes (likely). Further, movements will often be limited by a lack of natural land cover, and the presence of both natural and anthropogenic barriers (very likely).

3) One pro-active approach for helping a wide range of species adapt is to start by identifying large-scale patterns in projected exposure to climate change, and patterns in current factors that influence local-scale climate exposure (i.e., cooler lake-effect areas, streams fed by cold groundwater). When these climatic patterns are combined with maps indicating differences in key factors that correlate with differences in habitat conditions (soil type, slope and aspect, hydrologic factors), we can strive to protect a variety of conditions, or "stages", a goal which is associated with less uncertainty than one focused on protecting a particular list of species (or "actors" on the stages). In effect, one way to hedge our bets in favor of biodiversity is to focus on protecting and connecting a network of lands and waters that encompass the range of abiotic factors that together promote high diversity (i.e., a high variety of soil types/landforms, and hydrologic conditions); this approach should facilitate the persistence of higher numbers of species over the long term.

4) For freshwater and coastal species in the Midwest, it is particularly important to recognize the interaction between climate change, changes in land cover, and changes in hydrology. Land cover plays a very important role in determining the water and energy balance of a natural system. When vegetation is removed, or shows a major change in composition or structure, these balances tend to shift in ways that increase run-off, and promote flooding, both of which contribute to stressors that put sensitive species and habitats at risk (very likely).

5) When the natural systems that act to slow or store stormwater are protected and restored, both people and nature benefit. Pro-active partnerships can help reduce additional losses of these key systems and ecological services, and help anticipate and prevent actions that further disrupt our region's hydrologic balance.

Introduction

At a global scale, rapid changes in climate are expected to lead to increases in extinction risk across all types of life forms, and to reductions in the ability of natural systems to provide key services upon which human societies depend (Thomas et al. 2004, Field et al. 2007, Brook et al. 2008, Maclean and Wilson 2011, Bellard et al. 2012). The rate at which changes in temperature and other climate factors are occurring in the Midwest suggests that many, if not most, wild species and natural systems will experience climate change as a major stressor. Like other regions at moderate to high latitudes, climate change projections for the Midwest region are somewhat higher than projections for the global average. This region is also quite flat, suggesting that all but the most highly mobile species are unlikely to be able to move fast enough to "track" preferred climatic conditions, especially given that in many areas, much of the land has been converted to agriculture or urban/suburban land uses. For many species, including some that are able to show flexible responses within a limited range of temperature increases, genetic changes are likely to occur too slowly for natural selection to keep pace with the rapid warming in the environment. As species "fall behind" in terms of adapting to changing conditions, we are highly likely to see more examples of reductions in fitness, population declines, and eventual extinctions (Parmesan 2006, Foden et al. 2008). In addition, species that are able to adapt quickly to new conditions may put additional pressures (e.g., as competitors, predators, or parasites) on those that are not able to move or adapt, further accelerating the process of species loss (Parmesan 2006, Brook et al. 2008).

The high degree to which terrestrial and aquatic systems in the Midwest region have been altered by human actions makes it clear that as we frame our understanding of what species and ecosystem services are at risk, we need to think beyond the observed responses of natural systems. Given the current low proportion of natural land cover in the southern part of the Midwest region, the dominance of non-native invasive species in our aquatic systems, and impacts from pollution and barriers to movement, species lost from natural areas may only rarely be replaced with "native" species moving north. Thus, though the species and systems of the Midwest region may not stand out as being highly vulnerable to climate change when compared to species threatened by loss of polar ice cover, or loss of habitat due to sea level rise, the long-term viability of our species and systems may be at high relative risk due to climate-driven enhancement of existing stressors – the same stressors that have been the focus of decades of conservation and management efforts.

Linking climate impacts to species and system sensitivities

Observed changes, along with ecological theory, allow us to develop "rules of thumb" for how species are likely to respond to the most direct aspects of climate change (e.g., changes in air or water temperature). In addition, experimental studies and predictive models may provide clues as to how several climate factors (temperature, precipitation patterns) may interact, and we can weave these tools together with observations from both current and past climate changes to improve our understanding of vulnerability (Dawson et al. 2011). However, even when using a range of available tools, it is important to recognize that because many climate factors, habitat factors and ecological processes, and interacting species are often changing simultaneously, species and systems may show very complex responses, making it hard to categorize relative risk. Assessing the relative vulnerability of species become even more uncertain when we try to put climate change-related risks in the context of all of the other stressors that wild species and ecosystems currently face, such as habitat loss, invasion by non-native species, changes in hydrology, and pollution; and changes they will face in the future, including actions that societies take in response to changes in climate. Many researchers describe climate change as exacerbating current threats (e.g., Brook et al. 2008), a role that is likely to increase in importance and complexity as the rate of change continues to accelerate.

Understanding how climate change will impact species, systems, and ecological services is further complicated by the fact that several aspects of climate change involve feedback loops, or can impact species through multiple pathways. For example, water temperatures of the upper Great Lakes (Michigan, Huron, and Superior) are showing summer temperature increases that exceed regional temperature increases on land, in part due to positive feedbacks on the warming rate due to reductions in ice cover. Specifically, ice reflects energy from the sun, and insulates the water from the warming air, but melts more quickly when the air is warmer, and this loss of ice cover accelerates the rate of surface water warming (Austin and Colman 2007, 2008; Dobiesz and Lester 2009). Warmer waters can stress species because the increase in temperature reduces the oxygen holding capacity of water, and because at higher temperatures, the respiration rate of organisms, which determines how much oxygen is needed, is higher. These increases in temperature are triggering a whole range of system-wide impacts, including increases in wind and current speeds, and increases in the duration of the stratified period (Austin and Coleman 2007 & 2008; Desai et al. 2009; Dobiesz and Lester 2009). Predicting ecological responses to rapid changes would be challenging under any circumstances, but the fact that food webs and the flow of energy in Great Lakes systems are continually shifting as result of human-facilitated invasions by exotic species (Vander Zanden et al. 2010), makes understanding changes in these critical systems a particular challenge.

As with changes in temperature, there is little doubt that changes in precipitation have great potential to impact species, systems, and ecosystem services. However, at this time, it is much harder to make the case that changes in average precipitation, or seasonal patterns of precipitation, that have been, or may be observed are consistent with what is expected due to climate change. This is because long-term patterns of precipitation across space have tended to be more variable than temperature, and are associated with many short and long term cycles. In other words, while we know that too much or too little rain can lead to mortality or reduced fitness, it is often hard to detect a climate change signal within the “noise” of historic variation, and thus attribute observed changes in species that may result from precipitation changes to climate change as a key driver. Similarly, projections for precipitation amount and seasonal patterns tend to vary strongly across the suite of General Circulation Models used to evaluate possible future conditions. With respect to extreme precipitation events rather than mean values, however, there is general agreement that the frequency of extreme rain events (intense storms) will increase, especially in the winter and spring. Trends over the last 50 years for the upper Midwest suggest about a 30 percent increase in the amount of rain that falls in the top 1 percent of “very heavy” precipitation events, and this impact is expected to increase due to the fact that warmer air can hold more water (CCSP 2009, based on updates to Groisman et al. 2004, *new NCA refs?*). Climate change projections for the Midwest suggest continued increases in the frequency of days with storm events with greater than 1 inch of precipitation, with highest increases suggested for the frequency of the highest volume storms (Kunkel 2011).

When considering how to rank vulnerabilities, and respond to climate change in the Midwest and Great Lakes region, it is particularly important to understand the interaction between climate change and changes in land cover. Land cover plays a very important role in determining the water and energy balance of a system, in that vegetation cover slows water down, removes water from the system through evapotranspiration, and influences local temperature due to variations in albedo (reflectance) and by shading the ground surface. When vegetation is removed, or shows a major change in composition or structure, such as when forest is converted to agriculture, all of these relationships have the potential to change in ways that increase run-off, and promote flooding (Mao and Cherkauer 2009, Mishra et al. 2010). The impacts of these changes on aquatic systems can be quite strong, especially in landscapes with high proportions of agriculture or urban land uses, which act as sources of pollutants and fertilizers when large volumes of water flow across them into rivers and coastal areas. Further, the region has lost capacity to store water as a result of dramatic, large-scale draining and filling of wetland ecosystems. In the northern half of the region (MI, MN, and WI), estimates of conversion rates from circa 1780 surveys in comparison to 1980s Wetland Inventory Maps range from 42-50 percent, while in the southern Midwest region states (Illinois, Indiana, Iowa, and Ohio) losses are estimated at between 85-90 percent (Mitsch and Gosselink 2007, Appendix A). These diverse systems often occurred on areas with fertile soils that were drained for agriculture, although major cities like Chicago were also built upon drained wetlands. Thus, for the Midwest, changes to the timing, form (snow or rain), and amount of precipitation are acting on a system that is already highly altered in ways that tend to promote lower evapotranspiration and higher rates of surface run-off that leads to flooding. Although these systems can sometimes be restored, protection is critical. Even when we invest in restoring these critical systems, it is typical for important services and structural components to lag behind conservation goals based on conditions in less disturbed wetlands, even after a decade or two of restoration efforts (Moreno-Mateos et al. 2012).

Observed responses to temperature

A majority of wild species show predictable changes in responses to increasing temperatures, and the role of temperature in shaping species life histories is strong. In other words, temperature regime is a key element to which species have adapted over long (evolutionary) time periods. The potential effects of temperature changes are most apparent for ectothermic ("cold-blooded") animals such as insects, reptiles, and fish, for which body temperature, the key determinant of metabolic rate, strongly tracks the environmental temperature. For most ectotherms, these changes in internal temperature are associated with exponential increases in the rate of metabolic reactions that underlie body maintenance and growth (Deutsch et al. 2008, Zuo et al. 2011). Rates of key processes increase to an optimal threshold, after which they rapidly decline as organisms get closer to maximum temperature thresholds (Deutsch et al. 2008, Kearney et al. 2009).

At lower environmental temperatures, disruption in the availability of energy influences a wide array of physiological and behavioral traits, such as activity patterns and rates of growth and reproduction. In a warming Midwest region, research suggests that ectotherms like insects and reptiles will have longer active periods (prior to becoming dormant for the winter), and overall may experience higher fitness (Deutsch et al. 2008). However, metabolic costs will increase, especially for species that can not avoid higher temperatures through behavioral changes or movements, for example by moving to cooler microhabitats, or avoiding activity in the hottest parts of the day (Kearney et al. 2009). Homeothermic ("warm-blooded") animals—birds and mammals—maintain a relatively constant body temperature, but still can experience heat-related stress as temperatures continue to increase, especially when they inhabit areas where they are already close to thermal tolerance limits. As with ectotherms, there is some evidence that species that can moderate their exposure to climatic extremes through "sleep or hide" types of responses (hibernation or torpor during cold period, use or burrow or other shelters during the hottest part of the day) may be at reduced risk relative to other species with otherwise similar characteristics (Liow et al. 2009).

Plants also have temperature tolerances, though sensitivity to high temperatures is also strongly linked to water availability (i.e., drought stress). The seeds of some plants also require a period of cold temperatures so that they can germinate, suggesting that if that period is shortened as a result of warming minimum temperatures, fitness of some plants may be reduced. Similarly, some plants require a chilling period prior to budburst, and changes in climate may alter the pattern of bud and leaf development (Morin et al. 2009).

Although an increasingly wide array of responses and stresses on species and systems to temperature have been classified (e.g., Root et al. 2003, Parmesan 2006, Geyer et al. 2011, Maclean and

Wilson 2011) for the purposes of this review, I group responses into five basic types: 1) spatial shifts in ranges boundaries (e.g., moving north in the Midwest region); 2) spatial shifts in the density of individual animals or plants within various subsections of a species' range; 3), changes in phenology (the timing of events), such as when leaves emerge in spring, or when birds lay their eggs; 4) mismatches in the phenology of interacting species; and (5) changes in morphology and genetics. These categories are not mutually exclusive, as, for example, a change in the timing of bird migration can represent both a phenological shift, and a shift in gene frequencies (genetics).

Changes in species ranges and relative abundances

Shifts in where species occur can result from several different mechanisms. For many species, changes in climate conditions will enhance a given species' survival rate, growth rate, and/or reproductive rate in some parts of the species' range, and reduce one or more of these rates in other locations. Thus, even without dispersal (movement away from previously occupied habitats), these changes can lead to shifts in the subset of areas within a range where species are common, rare, or absent, and eventual changes in range. Changes in vital rates like survival can be linked back to the physiological constraints of balancing energy reserves under specific climatic conditions, as individuals in highly suitable climatic conditions will often have higher reproduction, survival, or both, than individuals in habitats that are more "costly" (e.g., higher cost of foraging due to heat or cold stress, higher metabolic rate due to higher water temperature for aquatic species).

For species to "track" changes in temperature by shifting ranges, they need to be mobile in some stage of their life history, and to have a suitable path to follow ("permeable" landcover, a freshwater system that is free of barriers). As a general rule, range shifts in response to warming temperatures result in species moving to higher latitudes or altitudes, although factors like lake effect, and topography, can modify local temperatures relative to large scale patterns (Klausmeyer et al. 2011, *more refs*). Movements in mobile species can be direct responses to temperature, such as fish seeking out deeper, colder water, or can be the result of natural selection acting on more random movements by populations of individuals, as those that become established in areas with more suitable climates are more likely to survive and reproduce. Similarly, for species like plants, which are rooted in one location, shifts in range occur as a result of a life stage like seeds being dispersed (e.g., by wind or birds) and becoming established in new areas that are now presumably more suitable than they had been in the past.

Although the rate of change is rapid in most parts of the world, species in the Midwest that respond by shifting ranges will need to move particularly fast to track climate change. The Midwest, and especially the upper Great Lakes region, has experienced a high rate of temperature change relative to other parts of the US that are at lower latitudes, and this trend of higher rates of change is projected to continue (REF – *need to add official ref for NCA climate data for all of US*). The combination of higher latitudes and relatively flat topography suggests that species "tracking" changes in temperature by shifting their ranges will require more rapid movement in this region than in other geographies where rates of temperature increase are lower, and/or where they could shift up in altitude to reach cooler habitats (Guralnick 2007, Jump et al. 2009, Loarie et al. 2009, Chen et al. 2011). In effect, the lack of topographic diversity in most parts of the Midwest can be thought of as increasing a species' exposure to climate change, or as a factor that reduces extrinsic adaptive capacity (i.e., the component of a species potential to adapt to changing conditions that is linked to its current environment, rather than intrinsic factors like traits or genetic diversity). For example, to reach areas that are 1 degree C cooler, a species in mountainous terrain could shift approximately 167 m in altitude, while achieving the same shift in flat terrain would mean a shift of roughly 145 km to the north (Jump et al. 2009).

A recent global study suggests that in most of the Midwest, tracking changes in temperature in the second half of the century (2050-2100, A1B emissions scenario) will require that terrestrial species move over 1 km/year; in comparison, the global average estimate "velocity" need to track change in terrestrial systems was less than half that rate, at 0.42/km year (Loarie et al. 2009). Similar estimates were attained in modeling work focuses on estimating the "temperature maintaining distance" for small mammals in northern Indiana: Fracl et al. (2010) suggest that to track changes in average January temperature that occurred during the mid 20th century, species would have needed to move north at between 0.4 and 2.1 km/year, with that estimate increasing in projections for this century. Rates of 1 km/year and higher are currently being achieved in some locations by some taxa (Chen et al. 2011), but are likely to be unattainable for many species, especially in highly modified landscapes. If emissions exceed the A1B scenario projections and are closer to A2, tracking change in the Midwest will require even faster movements (e.g., several km/year or more, Loarie et al. 2009 supplemental figure S17).

From a vulnerability standpoint, species that can move rapidly (e.g., birds) are typically seen as more likely to be able to keep up with climate change than other species with lower dispersal capacities (e.g., amphibians, most plants, sessile aquatic invertebrates), although of course birds and other mobile species depend on many plants and insects for food and shelter. In addition to moving north within river systems or large lakes, as noted above, some aquatic species also may be able to move into deeper, cooler waters within the same water body, although these deeper habitats may not have all of the other resources that a given species' requires.

Examples of species showing range and abundance changes in and near the Midwest region are beginning to accumulate, with the best documented examples coming from researchers conducting long-term research on topics such as community composition and population dynamics. Several recent papers document range shifts in birds, with changes dominated by northern shifts over a range of distances, and also some evidence for shifts in other directions (Zuckerberg et al. 2009 in New York state; Hitch and Leberg 2007 breeding ranges in North America, LaSorte and Thompson 2007 winter ranges in North America). Work by Myers and colleagues (2009) on mammals in Michigan documents rapid changes in ranges for several common species, including northern range edge shifts of over 225 kilometers since 1980 for white-footed mice (*Peromyscus leucopus*). Similar rates of movement appear to have been occurring with southern flying squirrels (*Glaucomys volans*), although the authors suggest that small, hard to detect populations may also have been rapidly expanding, and contributing to the shift in range (Myers et al. 2009). The movement of white-footed mice is of concern from a public health perspective, as these mice are key hosts for the ticks that carry Lyme disease (Ostfeld 1997). Brooks et al. (2005) also documented rapid northern shifts of southern flying squirrels in Ontario over a series of years with relatively warm winters and higher food availability (tree mast) – they document a 200 km northward shift over 9 years (1994-2003), but the range contracted to its historical limit following a very cold winter in 2004 that was associated with mast failure. The same research team documented a relative reduction in genetic diversity within squirrels trapped at the northern edge of this range expansion, providing evidence that even for species that can shift quickly, there may be fitness consequences associated with these rapid responses (Garroway et al. 2011). (*See also Handler et al's forest white paper for tree examples).*

Species are also showing changes in abundance within current ranges. Studies on moose (*Alces alces andersoni*) provide an indication of the complexity of the sensitive relationship between a species' population numbers and environmental temperature. Two separate research teams focused on understanding factors such as birth rates, parasite loads, and survival of moose in northwestern Minnesota (Murray et al. 2006), and on Isle Royale (Vucetich and Peterson 2004; Wilmers et al. 2006) suggest that warming temperatures are contributing to local population declines through increases in heat stress-related effects. Modeling by the Minnesota team suggests that, given the observed relationships between vital rates and temperature, the northwest Minnesota population of moose will not persist over the next 50 years (Murray et al. 2006).

As the examples above indicate, highly mobile species like birds and mammals are more likely than many others to be able to shift their ranges fairly rapidly; however, these movements have the potential to be slowed or blocked by inhospitable landscapes. In the Midwest, barriers for terrestrial species can range from natural features like the Great Lakes, to large expanses of agricultural fields or suburban/urban land use. Similarly, dispersal by aquatic species can be limited by the geography (e.g. east-west vs. north-south orientation) of the water body they inhabit, and by human-made barriers such as dams or road crossings with infrastructure that alters flow regimes or limits species movements. Ironically, in the Great Lakes region, some of the aquatic barriers have been put into place to protect aquatic systems from damaging invasive species like sea lamprey (*Petromyzon marinus*), so we can't simply remove them to help species move to more suitable habitats. *(Note to reviewers and author team – I am working on pulling together info on temp impacts on lamprey growth and control strategies to add to this document).*

When species are mobile and suitable habitat is present in the right location, range shifts may represent a viable response to changing conditions. However, range and abundance changes are of concern for several reasons. First, species that are not able to disperse will have the added stress of climatic conditions that are becoming less and less favorable, and by species that move in from warmer areas and are less challenged by the same climatic factors. The species moving in may directly compete for key resources, and also may contribute to the decline of resident species by spreading diseases and parasites. In addition to species that act as stressors on wild species of conservation concern, range shifts by species that act as forest or crop pests, or that are detrimental to public health (i.e., carry diseases, create toxic algal blooms) are key concerns in the Midwest, and are important subjects of observational and model-based research studies (e.g., Hong et al. 2007, Jactel et al. 2011). Further, many invasive, non-native species are likely to be more successful at invading and persist in our region as minimum winter temperatures continue to rise (Bierwagen et al. 2008, Vander Zanden et al. 2010). Third, we are concerned about range and abundance shifts because species movements will often be independent of shifts of other species. We expect species to shift independently, as the set of constraints that describe the habitat and ecological niche for each species (factors like temperature, food availability, soil types, and stream flow characteristics) is unique (Parmesan 2006). In effect, we expect to see the "tearing apart" of sets of species that typically interact, and many of these interactions may be critical to the survival one or more of the interacting species (Root and Schneider 2006).

Changes in phenology

In many species and systems, seasonal changes in temperature act as cues that trigger transitions in the seasonal cycles, such as metamorphosis (e.g., transition from egg to larvae), the development of new leaves, or the initiation of phytoplankton blooms that transfer energy through aquatic food webs. In addition to triggering changes in timing, known as changes in "phenology", warming trends can impact species indirectly by influencing other key seasonal events that trigger changes in their seasonal cycles, such as shifting the timing of snowmelt or flooding, or lake stratification.

Several early phenology studies that were highly influential in raising awareness that species were responding to changes in climate focused on, or included, study sites in or near the Midwest/Great Lakes region. These included evidence of 10 to 13 day advances in frog calling dates (an indicator of timing of breeding) in western New York in response to a 1 to 2.3°C increases in temperature in key months (Gibbs and Breish 2001), advances in the timing of many spring events (bird arrivals, plant blooming) on a Wisconsin farm in the 1980s and 1990s relative to observations taken by Aldo Leopold in the 1930s and 1940s (Bradley et al. 1999), and a nine day advance in the laying date of tree swallows (*Tachycineta bicolor*) across the continental U.S. over 32 years (1959-1991; Dunn and Winkler 1999).

Phenology changes can also be linked to indirect climate change impacts, such as timing of “ice-out” in spawning streams. Recent work by Schneider et al. (2011) suggests that both ice-out and walleye (*Sander vitreus*) spawning are occurring earlier in Minnesota. In most cases, the implications of change in phenology on fitness are unclear, but as we build longer term datasets in the Midwest, it is likely that patterns will continue to emerge. For example, a recent paper documenting long-term (approximately 100 years) changes in phenology and abundance of 429 plant species in Concord, Massachusetts (many of which are also found in this region) showed that although there has been an overall shift of 7 days in flowering phenology associated with a 2.4°C temperature increase in the study area, some plant families are showing less of a response to temperature than others (Willis et al. 2008). In many cases this failure to shift flowering time in response to changes in seasonal temperature was associated with strong declines in abundance (Willis et al. 2008).

Work by two teams of researchers that have documented climate-related changes in nesting patterns in freshwater turtles in Illinois over the past two decades (painted turtles *Chrysemys picta* - Schwanz and Janzen 2008; and red-eared sliders, *Chrysemys picta elegans* – Tucker et al. 2008) shows how complex predicting responses to climate can be. Like many reptiles, these turtles exhibit temperature-dependent sex determination, which means that the temperature at which the eggs are incubated determines the sex ratio of the eggs within the clutch. However, the relationship between air temperature and sex ratio is not simple, because vegetation cover can influence the nest temperature, and nests that are created early in the season may be in soils that are still cooler than ambient air (Tucker et al. 2008, Schwanz and Janzen 2008, Schwanz et al. 2010). In the study by Schwanz and Janzen (2008), initiation of nests has become earlier over time, with advances linked most strongly to years with warm winters; second and third clutches of eggs in the same season have also become more common. In the Tucker et al.’s (2008) work, the site has experienced a more consistent warming trend, and responses appear stronger; these include significantly earlier first nesting dates (2.23 days earlier per year), and a lengthening of the nesting season by 1.2 days per year between 1995-2006. As a result of these changes, especially the additional clutches per year, the total number of offspring in the Tucker et al. (2008) study has increased, with one surprising twist: Warmer temperatures produce more females in this species, but in recent years, the trend has been towards more males. The authors suggest that shifts towards earlier first clutches, plus a higher frequency of later season clutches, has meant more eggs developing under cooler soil conditions.

The term phenology mismatches describes situations where species that interact in some important way respond differently to a temperature change. The potential importance of mismatches may be easiest to imagine in systems where attainment of a threshold temperature cues the emergence of leaves of a dominant tree or grass, or algal growth. In such a system, a shift in the timing of spring warming that alters when these plants grow or bloom could represent a key change in the foundation of the food web that determines energy flows throughout that entire ecological system. If other species in the same system do not shift in the same direction and at a similar rate, they may be at a strong disadvantage in terms of their ability to survive and reproduce relative to other species.

As described above for fitness impacts, although wide variety of species are likely vulnerable to phenological mismatches, it is rare to have direct evidence that species are experiencing declining fitness through this mechanism. However, it is not very hard to pull together information to make the case that these types of changes should be of concern. For example, the northern Great Lakes region and the Mississippi River corridor stands out within North America for supporting vast numbers of birds during spring and fall migration. One group, songbirds, depend upon a ready source of insect prey, both along their migration routes, and in their breeding habitats. Studies in Europe have documented advances in insect emergence relative to bird arrivals at breeding habitats, and suggest that these timing mismatches are leading to reduced breeding (Visser et al. 2006; Both et al. 2009). In the U.S., Marra et al. (2005) compared the median capture dates of 15 long distance migrants from bird monitoring stations in coastal Louisiana and two stations in the Great Lakes region, Long Point Bird Observatory (on the north shore of Lake Erie) and Powdermill (western Pennsylvania). They also compared the duration of time between the median arrivals for the same species at the southern and northern sites. They found that median capture dates were earlier in years with warmer spring temperatures (mean April/May temperature) for almost all of their focal species, at a rate of roughly 1 day earlier per each 1°C increase in temperature. However, they note that in indicator plants (lilac, *Syringa vulgaris*), budburst occurred 3 days earlier for the same temperature increment, a similar rate to the average reported for plants in the Willis et al. (2008) study described above. Similarly, Strode (2003) suggests that North American wood warblers are not advancing in phenology as fast as key prey are likely to be responding to increased temperatures (e.g., the eastern spruce budworm, *Choristoneura fumiferana*). Earlier arrivals were at least in part achieved through faster migration (as opposed to earlier departure dates) as the duration of migration between the southern and northern locations decreased by 0.8 days with every 1°C increase (average of 22 days; Marra et al. 2005).

Changes in genetics and morphology

Most studies documenting responses to climate change focus on readily-observable characteristics such as phenological shifts; however, increasing numbers of studies are showing that changes in other characteristics, such as morphology (body shape or size), behavior, and underlying gene frequencies, can be linked to rapidly warming temperatures. As with other areas of response to climate, well-documented patterns that are not necessarily directly climate-related lead us to expect genetic impacts, such as well-documented patterns of reduced genetic diversity in populations at the "leading edge" of directional range expansions (Excoffier et al. 2009, Sexton et al. 2009; see also the Garroway et al. 2011 northern flying squirrel example cited above). Demonstrating changes in gene frequencies in response to climate change is a major challenge, as it requires these frequencies to have been measured in many generations. As a result, most examples are studies of short-lived insects like fruit flies (*Drosophila* species), and use comparative approaches. Work on fruit flies around the world has demonstrated shifts in how chromosomes are arranged that correlate with geographic patterns, i.e., populations in the north shift toward showing patterns like those to the south as climate warms (Levitan 2003; Balanyá et al. 2006; Etges and Levitan 2008). These changes tend to be discussed in terms of "heat tolerance," yet the actual benefit of these changes in terms of enhanced viability have not yet been established (Gienapp et al. 2008).

Strong evidence of similar genetic changes in vertebrates in response to climate change is very rare (Gienapp et al. 2008), but one notable exception comes from long-term research focused on red squirrels (*Tamiasciurus hudsonicus*) in western Canada. Work by Réale et al. (2003) demonstrated that shifts toward earlier breeding phenology in response to climate-induced changes in food supply are the result of both phenotypic plasticity (87 percent of the change) and an evolutionary response (13 percent). Recent work by Pergams and Lacy (2008) documented rapid genetic and morphological changes in Chicago-area mice (*Peromyscus leucopus*), though the mechanism for this change likely includes a complex set of environmental factors, in addition to recent climate changes.

Although results suggest that some species may be able to respond quickly to changes, many others may lack the genetic variation that might allow selection, and thus adaptation, to occur. In other cases, as has been demonstrated for a Minnesota population of a native prairie plant (*Chamaecrista fasciculata*), adaptive responses can be slowed even when variation is present, due to linkages between traits that are "antagonistic", such that one confers benefits in a new climate, and another does not (Etterson and Shaw 2001).

Changes in key processes

Due to strong overlap with the forest whitepaper and time constraints, I refer readers to page 6 of the forest white paper prepared by Handler et al. (February 2012 draft) for an overview of climate change impacts on key ecological processes and disturbance regimes in terrestrial systems.

Changes in temperature, both direct and through the ice and wind-related mechanisms described above in the impacts section, have the potential to profoundly change how large lakes in our region function. Specifically, these climate change factors may drive changes in the timing or duration of stratification. The differences in temperature, light availability, and other factors that occur as a result of stratification provide a diversity of habitats within stratified lakes, which allows species with a wide variety of temperature and other habitat requirements to persist. The timing of stratification, as well as the timing of the fall "turnover", when the oxygen-rich surface waters cool and increase in density, and finally sink down and mix with the others, can be a critical factor influencing the viability of lake species, especially cold-water fish. Given that changes in temperatures for the upper Great Lakes are projected to continue to match or exceed the air temperature increases, we should expect to see longer stratified periods and increased risk of oxygen deficits below the thermocline in late summer (Magnuson et al. 1997; Jones et al. 2006; Dobiesz and Lester 2009). Increases in the duration of the stratified period of over two weeks have already being observed for Lake Superior (Austin and Colman 2008), and projections for the end of this century suggest that we could see lakes stratify for an additional one and a half months (Lake Erie for a lower emissions scenario and thus less climate change) to three months (Lake Superior under the assumption of higher future emissions; Trumpickas et al. 2009). As the depth and latitude of a lake, lake basin, or bay decreases, it is less likely to show stratification, but some shallow water bodies will exhibit oxygen-poor "dead zones" because shallow water warms more rapidly, and warmer water holds less oxygen and leads to increases in respiration rates for aquatic species. As warming continues, we should expect more and more areas to develop "dead zones", and for others to transition from stratifying in summer to not stratifying at all, with resultant loss of species that depend on habitats characterized by colder water.

Linking observations to future changes

Thus far, the weight of evidence suggests that the most appropriate expectation for how species may respond to climate change is to anticipate more of the types of changes we have already seen -- i.e., changes in ranges (evading the change), and changes in phenology and behavior that allow species to persist in the same range. Not all changes in observed characteristics (phenotypes) that allow a species to persist in the same place require a change at the genetic level. Many species are able to show flexible responses to temperature as conditions vary among years. Thus, when conditions change in a given location, we can expect to both "flexible" changes in some species (phenotypic plasticity), and, if diversity is present and individuals that tolerate the conditions better reproduce more, heritable changes (evolution - a change in how common given genes are within the population). In general, phenotypic plasticity can be thought of as a "short-term" solution, as the limits to these responses will eventually be exceeded as a population experiences a long-term increase or decrease in an environmental factor (Gienapp et al. 2008). Thinking about both mechanisms for change highlights a caution for our ability to manage over the long term: Many species that appear to be tracking changes in climate, or thriving even as factors change, may show sudden declines in viability once the temperature shift exceeds some critical threshold beyond which their "flexible" response is not enough.

The potential for evolution in response to climate change is constrained by the degree to which genetic variation for particular traits is present in a given population (Holt 1990). vFor example, traits that contribute to increased heat or drought tolerance must be present in a population for natural selection to favor the individuals that have those traits, and eventually lead to an overall change in the proportion of individuals that have that "adaptive" trait in later generations. For many of Midwest's species of greatest conservation concern, we already suspect that population declines, habitat fragmentation, and other stressors have reduced the level of genetic variation such that there is little variation left upon which natural selection can act, however it is exceedingly rare to actually have data on genetics over time that can be used to confirm or refute this suspicion. Similarly, evidence for genetic responses to climate change is extremely rare, as it requires genetic data to have been sampled over time (Balanyá et al. 2006). As of yet, while there are many examples of changes in species in response to climate change, there are no documented examples of genetic shifts in thermal tolerances that appear to allow species to remain viable in the same location following a change that would have otherwise led to reduced survival or reproduction (Parmesan 2006; Bradshaw and Holzapfel 2008; Gienapp et al. 2008).

Assessing vulnerabilities

The vulnerability of a species, system, or ecological service can be described as a function of three factors: (1) exposure to some form of change in climate (e.g., temperature increase, change in timing of flooding); (2) sensitivity to the change, and (3) adaptive capacity, or the potential for that species, system, or process to respond, move, or even transform in a way that allows persistence or maintenance of key functions as conditions rapidly change (Schneider et al. 2007, Foden et al. 2008, Williams et al. 2008, Klausmeyer et al. 2011). While these categories are helpful from framing discussion, the concepts of sensitivity and adaptive capacity can be hard to disentangle in environments with a strong human influence. For example, a species or system may be much more sensitive to changes in hydrology (timing and amount of water availability) if invasive species, or drainage infrastructure, have already changed the way water moves through the system. For this reason, it is often helpful to think of both sensitivity and adaptive capacity in terms of intrinsic and extrinsic characteristics.

Intrinsic aspects of sensitivity include physiological tolerances for temperature or drought, while related intrinsic components of adaptive capacity include genetic diversity of a population (potential that some individuals have traits that lead to higher tolerances), and traits that allow movement or flexible timing for key life events. Following the temperature tolerance example, an animal may be more sensitive to increases in temperature if they are already stressed by some other factor, such as exposure to pollution or water with low levels of dissolved oxygen. Extrinsic elements of adaptive capacity include the geographic context in which the exposure to climate change takes place – for example, fish in deeper rivers or lakes are more likely to be able to persist as temperatures warm, because they can move into deeper water. Similarly, species that are likely to respond to changes in climate by shifting their range have higher intrinsic capacity to do so if they can fly or run, and higher extrinsic adaptive capacity to do so if they are currently found in a landscape or aquatic system that is connected to more northern habitats. From a management and conservation standpoint, we are typically trying to move "levers" that reduce the impact of extrinsic factors – can we reduce other stressors (like pollution or habitat loss) that increase sensitivity, or reduce adaptive capacity? Can we remove barriers to movement? Can we work with partners in other sectors to reduce changes in hydrology? However, in many if not most parts of the Midwest, there will be at least some species or system types for which there is little we can do to reduce the impacts of climate change; for these cases, reducing the rate of change through reduction of greenhouse gas emissions is the only meaningful strategy.

Characteristics often identified as indicators of species that are at greatest risk of population decline or possibly even extinction due to climate change impacts include (Parmesan 2006, Brook et al. 2008, Foden et al. 2008):

- Occur at high altitude or latitude (can't shift range further up or to the north in the Northern hemisphere).
- Occur in isolated habitats surrounded by developed land, or adjacent to natural barriers that inhibit dispersal.
- Near limits of physiological tolerance.
- Limited dispersal ability.
- Very specific habitat requirements, including ties to a particular timing of water availability.
- Highly dependent on interactions with one or a few other species (susceptible to phenology mismatches, and mismatches in rate or location of range shifts).
- Long generation time (slow potential pace of microevolution).
- Low genetic variability and/or low phenotypic plasticity.

Because the suite of potential impacts is so large, and impacts are often inter-related, our "best guesses" on impacts and species vulnerability may vary considerably depending on how many risk factors are considered. For example, Jones et al. (2006) found that projections of the potential impact of climate change on Lake Erie walleye (*Sander vitreum*) based simply on water temperature change were very different from results incorporating changes in climate-sensitive factors such as water levels and light penetration. This work relied upon decades of research on this fish's habitat needs and biology, and illustrates that for well-known species like walleye, the challenge to managers and conservation practitioners may focus on characterizing a complex set of direct and indirect climate-related changes that may interact and influence species survival. For most other species, a lack of baseline information from which to even begin the process of understanding potential impacts is often the most daunting challenge.

Considering the range of climate change drivers, and diversity of impacts described for both terrestrial and aquatic systems, it seems likely that one of our most challenging systems to protect will be Great Lakes coastal ecosystems. The region's Great Lakes coastal ecosystems have experienced dramatic changes due to accidental and intentional introductions of non-native species, and are already under stress from a wide range of factors (pollution, coastal development, reduced connectivity to streams and rivers). Due to their location at the interface between terrestrial and aquatic systems, coasts are susceptible to an unusually high number of climate-driven factors as well. In particular, interactions between invasive species, and increasing run-off from terrestrial systems during storms, combined with temperature increases in shallow waters and surface waters, and potential changes in wind and current directions, make understanding and responding to changes in these systems a major challenge. Yet, both the wild species and people of our region depend on productive, clean coastal systems as the base of food chains and local economies.

Helping species and systems adapt in the Midwest

Increase connectivity and "soften" management. Within the region, the ability of species to shift locations in space is likely to vary widely, both as a result of differences in movement ability, and as a function of the condition of the landscape or freshwater system (Parmesan 2006). In much of the Midwest, there are many barriers to movement, including both natural features like the Great Lakes, and vast expanses of land that may be inhospitable due to current land use (e.g., conversion to agriculture or other forms of development; Mitsch and Gosselink 2007, see Handler white paper for Forest Sector). A key goal for helping species and systems adapt in our region is improving connectivity by restoring natural habitats in areas where key connections have been lost, and by working to "soften" management in lands managed for multiple purposes, such that the ability of wild species to move through those areas is increased.

By increasing connectivity in both terrestrial and aquatic systems, we have the potential to increase the capacity of biodiversity to adapt to climate change through at least three mechanisms. First, restoring connectivity at local scales (i.e., connecting neighboring forest patches or stream reaches) increases the chances that genetic diversity in an area will be maintained by allowing increased mixing of populations. Higher rates of mixing, or "gene flow" should promote future populations with a wider range of variation in key traits (e.g., heat tolerance, growth rate under drought), increasing the odds that some individuals will be able to persist and thrive under new climatic conditions. Second, restoring connectivity can improve adaptive capacity by allowing mobile species access to cooler or moister microclimates (north facing hillsides, streams with high forest cover) within the same local area so that individuals can shift into these habitats when conditions are severe. Third, again for mobile species, increasing the connectivity of habitats provides a pathway for long-term shifts in range, as species shift north in our region to "track" their most favorable temperature regime. In addition to these three species-focused mechanisms, increasing the connectivity of ecological systems promotes resilience by allowing large scale ecological processes like flooding to occur, which provides essential mixing of energy and materials between aquatic and terrestrial systems. By restoring the connectivity of areas like floodplains and allowing this natural process to occur, we can also help people adapt to a key impact of climate change, increases in peak storm intensities, by reducing the risk of flooding of human-dominated lands.

For terrestrial animals, specific strategies include taking actions that enhance the likelihood that animals can move through our landscapes, such as restoring key habitats that have been lost, and working with landowners to enhance habitat values ("soften" management) on highly managed or modified lands. These types of actions should also benefit plants, which may be moved either by animals, or by wind. To help fish and other aquatic species respond by shifting ranges, we need to identify barriers in streams and rivers, and, balancing the risk of allowing access by invasive species (e.g., sea lamprey), take action to remove key barriers to northward movement. Understanding and developing responses to potential shifts in freshwater species are a particular challenge, because there is typically less information available on the distribution of aquatic species, and conservation areas are often more strongly tied to terrestrial, rather than aquatic, species diversity (Hieno et al 2009, Herbert et al. 2010).

Continue to pro-actively address the threat of invasives. In the upper Midwest/Great Lakes region, we have many native species, especially plants, which are best suited to survive and compete for resources when winter conditions are harsh and growing seasons are relatively short. As winter warms and the growing season extends, plants that can grow faster and can take advantage of these changes are likely to dominate, and likely will increase the rate of loss of the region's native species. These more competitive species may also be native, may be species from south of the region boundary, or may be non-native invasive species that have not been able to persist here before, but will be able to survive here in the future. While some changes in species are to be expected and even promoted as conditions change, to maintain overall plant diversity, we need to be even more vigilant about keeping potential invasive species from outside of North America from gaining a foothold. One strategy for this is to increase support for partnerships like Weed Management Cooperatives that focus on early detection and eradication, and increase investment in education-focused partnerships with key sources of non-native plants, such as the landscaping/gardening industry. Further, we need to be careful as we select seed and plant sources for restoration activities, as using seed sources from farther south in a species' range may make sense in some situations if we want to be pro-active, but may contribute to declines in rare local populations if planted in proximity to locally produced plants (Holmstrom et al. 2009)

<u>Shifting some of our conservation attention from species to "stages."</u> Historically, efforts to identify key places to conserve to protect biodiversity have focused on mapping patterns of where species are found, and choosing to purchase or protect areas based on "hot spots" suggested by these distributions. Given that many species are likely to shift distributions in response to changing conditions, and that individual species' responses to climate change will be complex and individualistic (Root and Schneider 2006, Chen et al. 2011), to protect the largest number of species, we need to think beyond individual species responses. This perspective of moving from a focus on species toward a focus on systems or landscapes/watersheds is not new, but takes on a higher importance, and includes some additional elements (saving the "stage" and protecting climatic refugia) as we update conservation and management to incorporate climate change (Groves et al. in press). Specifically, a key strategy for "climate smart" biodiversity conservation involves broadening our perspective from species to think about the diversity of conditions on landscapes and watersheds. As we prioritize areas for protection, consistent patterns of variation in climate factors should be recognized and integrated with consistent patterns in drivers of biodiversity (e.g., variation in geomorphology, hydrology – Anderson and Feree 2010, Beir and Brost 2010). These consistent landscape-scale units of variation have been referred to as "stages" (in the sense of a location where actors, or species, might appear – Anderson and Feree 2010) or "land facets" (Beir and Brost 2010). If we can map these stages or land facets, we can focus land protection or conservation efforts on capturing the widest possible variety of these land or aquatic units. When these gradients are protected, we maximize the potential for heat-stressed individuals of a wide range of species to encounter cooler micro-sites without having to move long distances. Further, adapting our conservation work to include the goal of capturing the range of factors that underlie variation in species should help protect a wider range of species within taxa that are typically not represented as conservation areas are designated, such as mollusks and other invertebrates (Ledeard et al. 2004).

In the Midwest, one element of capturing the breadth of land facets or stages to conserve will involve increasing our understanding of how exposure to climate change varies across landscapes, stream networks, and within large lakes and rivers. Individuals of a species respond to the climate they experience, not average conditions (Walther et al. 2002), and what they experience varies with factors like latitude, landform, distance from a Great Lake, and water source (groundwater or surface water; Andersen and Feree 2010, Beir and Brost 2010, Klausmeyer et al. 2011, Magness et al. 2011). Thus, a key step toward updating our approach to conservation involves answering questions like: "What factors influence the spatial distribution of warming?" Once we have a better understanding of current variation, we can develop conservation strategies that take advantage of naturally cooler areas, or climate "refugia", such as the cooling influence of the Great Lakes on nearby terrestrials systems, and do a better job of protecting the thermal regime of streams (keeping riparian vegetation intact, minimizing exposure to stormwater that has been heated up through exposure to pavement) (Groves et al. in press).

Protect people and nature by restoring functional ecosystems in watersheds dominated by agriculture. Direct and indirect impacts of climate change have great potential to reduce the effectiveness of conservation strategies focused on protecting rivers and streams in watersheds dominated by agriculture. First, these systems will be affected by temperature changes, and are highly sensitive to changes in the timing of and amount of precipitation. Further, an increase in the intensity of peak storm events (Kunkel 2011) suggests an increase in some of the most important current threats. For example, big storms, especially storms that occur when soils are saturated, lead to overland movement of sediments and pollution from agricultural fields into streams, which can drastically reduce the suitability of these systems for the region's native fish and invertebrates (Sowa et al. 2007, Herbert et al. 2010). Partnerships with the agricultural sector are likely to be a key component of conservation success, as responses by farmers to changes in the climate can also put sensitive species and aquatic systems at greater risk. For example, increases in temperature influence what farmers can grow, extends the length of the growing season, and also leads to increased evaporation, which promotes drought stress and reduced stream flows. In some places, increased drought stress may promote increased investments in irrigation, and resultant stresses on ground and surface water supplies.

Interactions with water are likely even more important in the spring: In many watersheds, farms have very effective systems for quickly shunting spring precipitation off of fields to allow earlier planting of crops. As the intensity of storms continues to increase, we expect to see more farmers adding to their drainage infrastructure. However, drainage, and the simple conversion of land to forms that have low capacity to absorb water, or slow the overland flow of water, promotes flooding of all sorts of land types, including farms, residential areas, and cities. One key strategy for reducing the risk of flooding is to work in partnership with the agricultural sector to reconnect and re-vegetate natural floodplains along streams and rivers. Natural floodplains provide the essential services of holding and absorbing flood waters which protects people and property, and also promote connectivity for a wide variety of species that use them as corridors through what is often an inhospitable landscape.

Similarly, increases in peak storm events increase the odds that combined sewage and stormwater systems will overflow into coastal areas, releasing a wide range of pollutants into coastal systems. Natural systems are at risk from these changes, but can also be a key part of the solution – by increasing the proportion of forests, wetlands and other natural systems in areas prone to flooding, water can be slowed down and held, reducing the risk to both aquatic systems, and to people (Kousky et al. 2011). This approach is supported by research showing how hydrology in the Upper Great Lakes region has changed as a result of large-scale conversion of forests into agriculture and other forms of lands use with lower rates of evapotranspiration and infiltration (Mao and Cherkauer 2009, Mishra et al. 2010). As climate change continues, we will need to be much more pro-active in how we address issues related to storms and flooding. Further, successful adaptation will require collaborative solutions, as decisions made in one sector, such as increasing the amount of drainage infrastructure in agricultural systems in response to wetter springs, can put both nature, and the people downstream, at greater risk of flood-related impacts. To reduce the problem of flooding, and pro-actively prepare for increases in storm intensities, restoring systems like forests and wetlands in flood prone areas are essential components of adaptation strategies to benefit people and nature.

Most opportunities and potential benefits to biodiversity from engaging with actions taken in other sectors are not new, but they may now rise in importance, as we expect adaptive actions to take place in these sectors. A good example of a persistent stressor that fits this description are overflows of combined sewer and stormwater handling systems in which rainwater, sewage, and industrial wastewater are transported in the same pipe and to sewage treatment plants, where water is treated and discharged to a water body. At this time approximately 746 cities in the US (U.S. EPA 2004 and 2008; references include a map) have combined sewer systems, and many of these are in the upper Midwest. Heavy rain or rapid snowmelt, both of which are predicted to be enhanced in the Great Lakes region can lead to overflow, which means direct discharge of wastewater into water bodies. Overflows are a threat to both water quality and public health, as output can include microbial pathogens, suspended solids, biochemical oxygen demand (BOD), toxic materials, nutrients, and debris (US EPA 2004). In many locations, infrastructure for handling wastewater is need of updating, and sectoral climate change vulnerability assessments emphasize the need to plan for increases in stormwater volume (U.S. EPA 2008). When updates to these systems are planned, the conservation community can play important roles in promoting the implementation of "green infrastructure" (e.g., wetland restoration, riparian buffers, rain gardens), and in ensuring risks to biodiversity are accounted for as new standards and policies for these systems are put into place.

As we work to update our conservation plans and make them "climate smart", it is vitally important that we also update or approaches to management such that they become more agile, and able to shift strategies quickly in the face of new information and surprises. With respect to anticipating surprises, we expect that surprises for resource managers will take at least three forms: 1) Exceedance of thresholds (e.g., thermal tolerance thresholds, leading to strong declines in fitness); 2) new interactions among species, and/or new or synergistic impacts related to interactions with climate and other stressors (e.g. invasive species); and (3) higher frequency of extreme weather events with catastrophic impacts on focal systems (floods, ice storms, extreme cold periods in spring).

Acting in a climate smart way will also require that we improve our ability to share and synthesize the information we do have, and improve our tools for acting in the face of uncertainty. We will also need to do a better job of separating scientific data from values, and work more closely with a broader range of stakeholders to craft cross-sector solutions (Hobbs et al. 2010, Groves et al. *in press*). Evidence that addressing climate change helps promote larger-scale approaches to conservation can be seen in the recent emergence of many regional scale collaborations, including a recent agreement between the states of Michigan and Wisconsin to share information and work together on adaptation, and a suite of federal initiatives, including USFWS's Landscape Conservation Cooperatives, NOAA's Regional Integrated Sciences and Assessments teams, USGS's Regional Climate Hubs, and the USFS's Shared Landscape Initiative. Given all of these new opportunities, we need to be ready to pursue actions that improve conservation more broadly by improving communication, collaboration, and connectedness of efforts. Although encouraging in many respects, this growing list of entities that seek to lead on climate change through creating regional partnerships suggests that while key agencies agree on an appropriate scale for consideration of the challenge, we face a major coordination challenge.

Note to authors -- Possible case study: "The Role of Land Use in Adaptation to Increased Precipitation and Flooding: A Case Study in Wisconsin's Lower Fox River Basin." Kousky et al. (2011).

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Climate Change Vulnerabilities within the Forestry Sector for the Midwestern United States

White Paper Submission to the Midwest Technical Input Team for consideration in the Midwest Chapter of the National Climate Assessment

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Highlights:

The statements below represent our assessment of potential ecosystem responses and vulnerabilities to a range of projected future climatic changes within the Forestry Sector of the Midwest Region of the United States. Although some impacts have already been observed, we attempt to provide information that will help decision makers evaluate climate-related vulnerabilities through the end of the century.

Key Vulnerabilities across the Midwest Region:

1. Climate change will amplify many **existing stressors** to forest ecosystems (very likely).
2. Climate change will result in **ecosystem shifts and conversions** (likely).
3. Many tree species will **not be able to migrate** sufficiently to keep pace with climate change (likely).
4. Climate change will amplify existing stressors to **urban forests** (very likely).
5. Forests will be less able to provide a consistent supply of some **forest products** (likely).
6. Many forested watersheds will be less able to produce reliable supplies of **clean water** (likely).
7. **Carbon storage** in many forest ecosystems will be reduced, primarily due to episodic events and through interactions between climate and multiple stressors (possible).
8. Many contemporary and iconic forms of **recreation** within forest ecosystems will change in extent and timing (very likely).
9. Traditional and modern **cultural connections** to forest ecosystems will be altered (likely).

Contents

Organization of white paper

This white paper on the Forestry Sector was prepared as an input to the National Climate Assessment (NCA; http://www.globalchange.gov/what-we-do/assessment). Specifically, this paper is a contribution to the Midwest Technical Input Team, which will be integrated into the Midwest Chapter of the NCA. Therefore, we have followed guidelines related to framing key conclusions, communicating uncertainty, and information quality as presented by the NCA Development and Advisory Committee. The guidelines for technical input and author teams can be viewed here: http://www.globalchange.gov/what-we-do/assessment/nca-activities/guidance.

We have organized this white paper to enable the Midwest Technical Input Team to easily identify priority themes and key vulnerabilities. We draw a distinction between vulnerabilities related to forest ecosystems (Forest Ecosystems), and the vulnerabilities that are related to ecosystem services derived from forests (Benefits from Forests). We categorize Urban Forests as a distinct category of Forested Ecosystems, because of specific risks, consequences, and vulnerabilities associated with these types of forests. The section on Adaptation describes general concepts and actions for responding to these vulnerabilities.

Each "key vulnerability" statement is followed by our qualitative view of its likelihood of occurring, using specific language established by the Intergovernmental Panel on Climate Change (Backlund, Janetos, and Schimel 2008; Intergovernmental Panel on Climate Change 2005). Our use of these confidence statements is similar to Backlund, Janetos, and Schimel (2008); the statements reflect our judgment as authors and we have not applied this terminology to previously published studies. Figure 1 presents the spectrum of confidence terms used in this white paper.

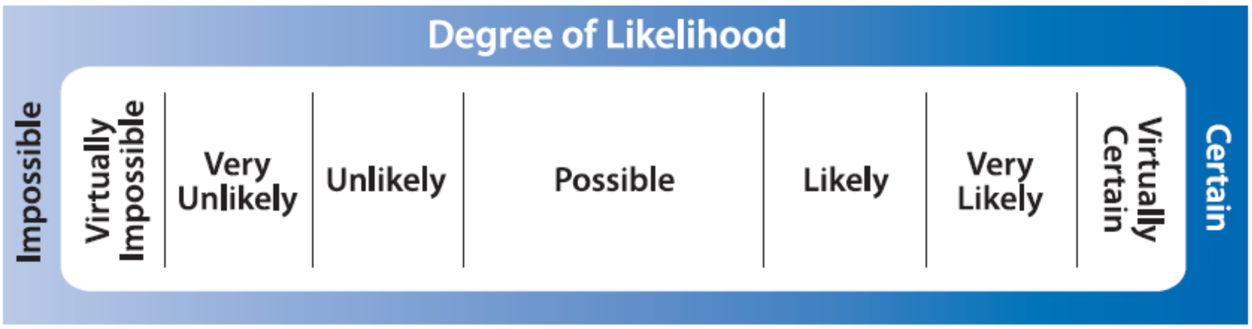


Figure 1: Language for describing confidence in findings, from Backlund, Janetos, and Schimel (2008).

Although we are synthesizing research that utilizes numerous global circulation models, future climate scenarios, and downscaling methods, we will attempt to refer to the standard set of climate projections prepared for the Midwest Region for the National Climate Assessment (Kunkel 2011). These projections rely on a suite of climate model simulations using the B1 and A2 emissions scenarios as "low" and "high" climate futures, respectively (Kunkel 2011).

Introduction

Forests are a defining landscape feature for much of the Midwest, from boreal forests surrounding the northern Great Lakes to oak-hickory forests blanketing the Ozarks. Savannahs and open woodlands within this region mark a major transition zone between forest and grassland biomes within the United States. Forests help sustain human communities in the region, ecologically, economically, and culturally.

Climate change is anticipated to have a pervasive influence on forests in this region over the coming decades. In recent years, a growing field of study has emerged to categorize and predict the consequences of climate-related changes in forest systems (Glick et al. 2011; Swanston et al. 2011; Parry, Canziani, and Palutikof 2007; Fischlin et al. 2009; Schwartz et al. 2006; Clark et al. 2011). Two metrics that are often used to assess the outcome of climate-related changes in natural systems are "vulnerability" and "risk." In this paper, we define vulnerability as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes" (Intergovernmental Panel on Climate Change 2007). Vulnerability is a function of the degree of climate change that a system is exposed to, as well as the system's sensitivity and capacity to adapt (Swanston et al. 2011; Glick, Stein, and Edelson 2011; Glick et al. 2011). Also, it is important to note that vulnerability can refer to a decline in vigor and productivity, in addition to more severely altered community composition or ecosystem function (Swanston et al. 2011). That is to say, a species or ecosystem may be considered vulnerable to climate change by virtue of decreased well-being even it is not projected to disappear completely from the landscape.

Risk offers an additional approach to describing the potential consequences of climate change in forest ecosystems. Risk includes an estimate of the likelihood or probability of an event occurring, in combination with the consequences or severity of impacts of that event (Glick et al. 2011). This approach explicitly considers uncertainty, although clearly communicating uncertainties is necessary for describing both vulnerability and risk in the context of natural resource planning.

This white paper summarizes recent information related to the major potential vulnerabilities associated with climate change in the forestry sector, organized according to "key vulnerabilities." For the purposes of this white paper, key vulnerabilities are those that have particular importance due to the anticipated magnitude, timing, persistence, irreversibility, distributional aspects, likelihood, and/or perceived importance. Rather than attempting to quantify these risks, this assessment focuses on the question, "What is at risk?" This paper does not attempt to make new estimations of vulnerability or risk for the forestry sector, but rather will synthesize recent information to provide a useful summary.

The Midwest Region, as defined for the purposes of the NCA, covers the states of Minnesota, Wisconsin, Michigan, Iowa, Missouri, Illinois, Indiana, and Ohio. Forest ecosystems are not organized along political boundaries, but are distributed according to patterns of climate, moisture, soils, and disturbance. Therefore, we present information on key climate change-related vulnerabilities according to ecological regions (ecoregions), as defined by Bailey et al. (1995). The Midwest's 8-state footprint includes five distinct ecoregions, which are delineated according to associations of biotic and environmental factors that determine the structure and function of ecosystems (Figure 2). The species, disturbance regimes, existing stressors, and potential exposure to climate change are different for each of these ecoregions. Therefore, we present key vulnerabilities that capture broad concerns across the Midwest and include ecoregion-specific information for greater depth and context where available.

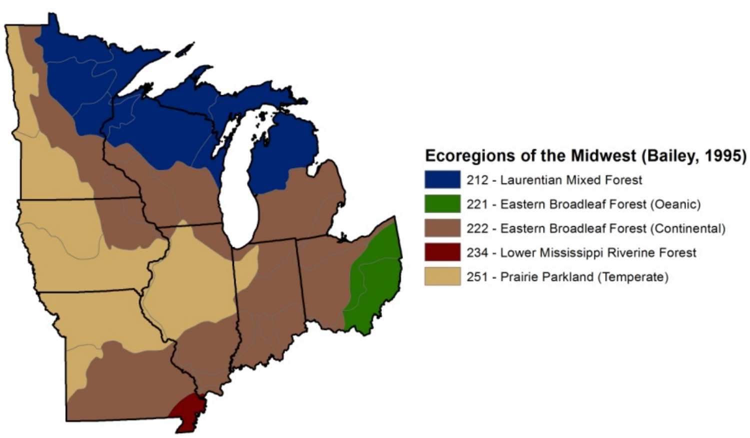


Figure 2: Ecoregions within the Midwest Region, according to Bailey et al (1994).

Because of the numerous connections between the forestry sector, other elements of the natural environment, and other sectors of human activity, there is necessarily some overlap between this white paper and other papers being prepared for the Midwest Chapter of the NCA. Readers who are interested in these connections may find supplementary information in other white papers prepared for the Midwest Chapter of the NCA, or in sector-specific chapters of the larger NCA.

Forest Ecosystems

Key Vulnerabilities across the Midwest Region

This section covers broad key vulnerabilities that are expected to be common to forest ecosystems across the entire Midwest Region. We have divided these region-wide vulnerabilities between "Forest Ecosystems" and "Urban Forests."

Forest Ecosystems

1. ***Key Vulnerability: Climate change will amplify many existing stressors to forest ecosystems (very likely).***

Forest ecosystems throughout the Midwest Region are exposed to a range of natural, introduced, and anthropogenic stressors. These include invasive flora and fauna, natural and exotic pests and diseases, altered disturbance regimes, land-use change, fragmentation, atmospheric pollutants, and others. Decades of research has revealed numerous individual and combined effects of many of these stressors on a variety of forest types. A more recent and rapidly growing area of this research, including experimental, observational, and modeling studies, includes the interaction of changing climate with existing stressors.

Anthropogenic changes in forest ecosystems are diverse and pervasive throughout the Midwest Region, including land conversion, fragmentation, timber harvesting, and fire suppression (Minnesota Department of Natural Resources 2010; Flickinger 2010). The Midwest has experienced large reductions in forest cover from pre-European settlement to the present, with the most dramatic declines occurring in Ohio (95% forest cover reduced to 30.2%) and Illinois (40% forest cover reduced to 13%) (Ohio Department of Natural Resources 2010; Illinios Department of Natural Resources 2010). In general, these impacts have reduced diversity across forest ecosystems (Nowacki and Abrams 2008). Open woodlands and savannahs have been lost to agricultural expansion and fire suppression, while fragmentation has reduced overall forest patch size and resulted in more edge habitats (Radeloff, Hammer, and Stewart 2005; Nowacki and Abrams 2008). Population growth has occurred in tandem with these changes. Between the year 1900 and 2000, the ratio of people per square mile of forest in nearly doubled for four states (Indiana, Iowa, Missouri, and Ohio), tripled for two states (Michigan and Wisconsin), and increased by a factor of 15 for Illinois (Barnes et al. 2009).

The Midwest Region stands out as one of the most concentrated areas of ecosystem conversion and alteration in the country. A recent analysis by Swaty et al. (2011) highlighted this trend by integrating the combined effects of outright land conversion with the more subtle influences of fire suppression and forest management. Several studies from around the globe have illustrated the negative influence that habitat fragmentation will likely have on range expansion and colonization of new habitats by a variety of tree species (Iverson, Schwartz, and Prasad 2004; Honnay et al. 2002; Scheller and Mladenoff 2008).

Climate change is also changing the disturbance regimes that influence forest ecosystems, including fire occurrence and severity, drought, floods, ice storms, and windstorms (Dale et al. 2001). Droughts and moisture limitations on forest ecosystems are projected to be more common by mid-century under the likely future climate scenarios, as growing seasons extend, summer temperatures increase, and precipitation patterns change (Hanson and Weltzin 2000). Cherkauer and Sinha (2010) examined streamflow patterns based on downscaled climate projections in four states surrounding Lake Michigan, and found that summer low flows decreased, summer high flows increased, and overall flashiness increased in summer months. When overlaid with projected increases in temperature for the region (Kunkel 2011), these projections suggest increased potential for late-summer droughts and decreased moisture availability for forests, particularly at the end of the growing season. The consequence of moisture stress on forest ecosystems depends on a range of factors, but this disturbance can lead to substantial declines in productivity and increases in mortality. This is especially the case for seedlings, drought-intolerant species, and drought-intolerant forest types (Hanson and Weltzin 2000).

Among natural disturbances, fire has been the most manageable, and fire suppression is likely to continue for most of the Midwest Region. The maximum duration of multi-day periods with temperatures >95°F is projected to increase by 85-245% across the entire Midwest Region by mid-century, according to a range of climate projections (Kunkel 2011). A greater frequency of high-temperature days, in combination with dry late summer conditions, could lead to more active fire seasons across the region (Bowman et al. 2009). Increased investment in fire suppression and preparedness would likely minimize impacts to ecosystems for some time, but future decades may see much greater fire severity as seen in modeling projections (Lenihan et al. 2008) and western examples of near-term stress combined with long-term fire suppression (Peterson et al. 2005).

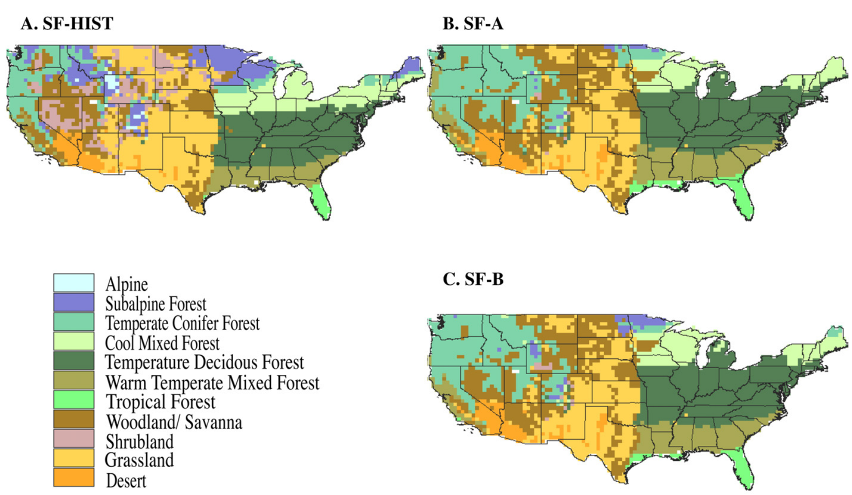
Dukes et al. (2009) reviewed the state of knowledge regarding climate change on insect pests, pathogens, and nuisance plant species, and on the resulting impacts on forest ecosystems throughout the eastern half of the US. Under the A2 emissions scenario, they forecast more insect pest damage due to increased metabolic activity in active periods and increased winter survival, although effects of climate on forest insects remain uncertain. It is more difficult to anticipate the response of forest pathogens under a warmer future due to complex modes of infection, transmission, survival, and tree response. Invasive plants are generally expected to "disproportionally benefit" due to tolerance for adapting to changed environments and more aggressively colonizing new areas. In each case, uncertainty limited the ability of the researchers to make confident predictions.

Kling et al. (2003) also reviewed interactions between forest inspect pests, atmospheric pollutants, elevated CO2, and climate change. They suggested increased drought stress may make forests more susceptible to both fires and pests, but elevated CO_2 could speed forest succession after these disturbances. They anticipated, however, that ground-level ozone could counteract any short-term increase in forest growth due to elevated CO_2 or nitrogen deposition. Additionally, changes in phenology due to climate change could result in timing mismatches with insect pests as well as pollinators. The interactions are complex, with some ecosystems potentially experiencing increases in forest health and vigor, while others are more likely to show a loss of ecological function or identity. Less diverse forests are generally considered more vulnerable to climate change if they are at all maladapted (Swanston et al. 2011), and may warrant greater scrutiny as systemic changes to stressors become more manifest.

2. Key Vulnerability: Climate change will result in ecosystem shifts and conversions (likely).

As temperature and precipitation patterns continue to change, it is possible that large ecosystem shifts and conversions will accompany the changes. Ecosystems are complex assemblages of species, and so the response of individual species will strongly affect how ecosystems respond as a whole. Additionally, climate pressure on changing forest will continue within the context of forest management, possibly including active and widespread adaptation efforts. Changes in broad ecosystem types will thus vary from one place to another based on local management decisions specific influences of site-level environmental factors.

Examination of simulated ecosystem responses to a range of climate projections can be used to assess large-scale trends that may be expected in forest systems. Lenihan et al. (2008) used the dynamic vegetation model MC1 to examine potential changes in vegetation classes at the end of the 21st century due to climate change and fire suppression across the US (Figure 3). Under future emissions scenarios comparable to Kunkel (2011) with continued fire suppression, they projected that the Midwest Region would lose most boreal (labeled subalpine) forests, with a majority of the region transitioning to a temperate deciduous forest (SF-A and SF-B, Figure 3). In future scenarios with more wildfire activity the boreal forest types were similarly diminished in the Midwest Region, but they were replaced in western portions of the region by woodlands, savannahs, and grasslands. Temperate deciduous forests were projected to move northward and occupy much of Indiana, Ohio, and Michigan under both high (USF-A) and low (USF-B) emissions scenarios.



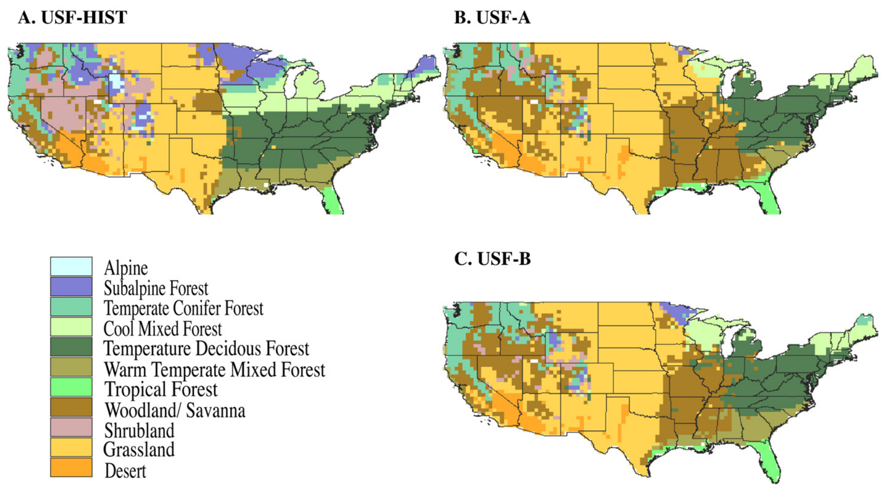


Figure 3: Model simulated vegetation type with suppressed fire (SF) for 1971–2000 historical period (HIST) and 2070–2099 future period. A: SRES-A2 emissions scenario (high climate change), B: SRES-B2 emissions scenario (low climate change). From Lenihan et al. (2008).

Simulation results from Lenihan et al. (2008) also showed a large expansion of woodland/savanna and grassland vegetation types in the Midwest under the unsuppressed fire scenarios (Fig. 3: USF-A and USF-B). This work is largely consistent with results from the systems mapping approach of Frelich and Reich (2010), which showed a broad shift from forest to savanna along the prairie-forest border in the Midwest. The systems mapping approach did not include explicit consideration of fire suppression. These studies illustrate the potential for major shifts in vegetation types even under lower emissions scenarios, but also that societal investment into management efforts such as fire suppression may have equally strong influence.

When considering the potential for changes to vegetation types, species' migration is a critical issue. It is not necessarily communities that move, but instead species that move and then form new communities. Re-constructions of vegetation response to past climate change indicate that the species forming forest communities have disassembled and re-aggregated in different permutations (Davis, Shaw, and Etterson 2005). Species distribution models have also indicated that species may respond individually to future climate change, with suitable habitat expanding for some species and declining for others (Iverson, Prasad, and Matthews 2008; Morin, Viner, and Chuine 2008; Walker, Davis, and Sugita 2002). Despite a high degree of fragmentation in natural ecosystems across the Midwest, widespread vegetation migration may occur in response to the degree of climate change that is projected. For the majority of 134 tree species across the eastern US, the Climate Change Atlas estimates that mean centers of suitable habitat will migrate between 100-600 km to the northeast under a high emissions scenario and between 50-400 km under a more mild climate change scenario (Prasad et al. 2007-ongoing). Similarly, a distribution model based on phenological timing projects a general northward expansion among 14 widespread Midwestern tree species, with local extinctions at southern range extents (Morin, Viner, and Chuine 2008). The interacting factors of potentially novel sub-regional climates, habitat fragmentation, and widespread forest mangement with the possiblity of increasing focus on adaptation will greatly influence how species migrate, colonize, or survive in current and future habitats, raising the possibility that unprecedented assemblages of species could form novel ecosystems.

3. ***Key Vulnerability: Many tree species will not be able to migrate sufficiently to keep pace with climate change (likely).***

Analysis of forest species response to past climatic change has highlighted the fact that contemporary rates of temperature change will make it very difficult for trees to migrate fast enough to track changes (Davis 1989; Davis, Shaw, and Etterson 2005). Newer studies utilizing species distribution models have projected that tree species in the eastern US have a low probability of colonizing habitat beyond their existing ranges over the next 100 years (Iverson, Schwartz, and Prasad 2004). Habitat loss and forest fragmentation are two primary reasons for this expected inability to migrate, with the actual movement of tree species being substantially slower compared to the shifts in optimum latitudes based on temperature and precipitation. Iverson et al. (2004) estimated that less than 15% of newly available habitat would be colonized over 100 years in a study of five eastern tree species, using future temperature projections similar to Kunkel (2011).

Studies are beginning to emerge that examine whether observed tree distribution in the near term matches the anticipated trends. These studies largely serve as a reminder to avoid an oversimplified view of northward range shifts. Some work has found evidence of an expansion northward of northern species, with less evidence of a strong response by southern species (Woodall et al. 2009), but northward range expansions may be limited to a small percentage of species (Zhu et al. 2011). Range contractions along the southern edge of several species' distributions have also been documented (Zhu et al. 2011, Murphy et al. 2010). Based on gathered data on seedling distributions, Woodall et al. (2009) estimated that many northern tree species could possibly migrate northward at a rate of 100km per century. This study also raised the possibility that human-facilitated migration could allow more rapid speciees movement.

Plants that are "left behind" by a shifting habitat will not necessarily become extirpated from a site, especially if there are no better-adapted species to out-compete them. Better-adapted species may fail to successfully migrate and establish due to several factors, such as habitat fragmentation or land-use change, or moisture patterns (Iverson, Schwartz, and Prasad 2004; Honnay et al. 2002; Scheller and Mladenoff 2008; Crimmins et al. 2011). Even without strong competitors, plants living outside their suitable habitat may decline in vigor or have lower resilience to a variety of stressors. In the long run, ecosystem shifts may take place not through climate-related mortality, but instead through poor recruitment of young trees.

Urban Forests

4. ***Key Vulnerability: Climate change will amplify existing stressors to urban forests (very likely).***

Urban forests are distinct from natural or managed forest ecosystems, partly because of their structure and composition, and partly because of the many specialized benefits they provide for residents of cities and towns.

Urban areas occupy 3.9% of the total land area in the Midwest, with an average tree cover of 33.2% (Nowak and Crane 2002). This is a higher proportion of tree cover than the US average, and the second highest proportion among all the major regions of the country. Forests in metropolitan areas typically occur in unnatural mixed assemblages with ornamental and understory species (Woodall et al. 2010). These forests usually have 50-80% less biomass per-area than is typical in forest areas. While large numbers of different species may occur in urban settings, a few primary species represent the majority of trees. The state of Indiana illustrates this pattern, with maple and ash species making up the bulk of trees found within municipalities and 3 of the top 11 most frequent species being non-native to the state (Indiana Department of Natural Resources 2010). Benefits of urban forests include decreased heating and cooling demands for neighboring buildings; recreational opportunities found within urban green spaces and trails; and mental, physical, and emotional well-being of the general public (Younger et al. 2008; Nowak and Crane 2002; McPherson et al. 1997). These specialized values are important in large metropolitan areas as well as smaller communities throughout the Midwest Region.

Climate change will have direct and indirect consequences for urban forests. Climate change is expected to amplify existing stressors that urban forest communities currently face, similar to forests in natural environments. Expected consequences of climate change include increased activity of insect pests and diseases, more frequent exposure to heat waves and drought, and phenological mismatches with pollinators and dispersal agents. Additional stresses faced by urban forests include increased atmospheric pollution, heat island effects, salt damage, highly variable hydrologic regimes, and frequent exposure to novel pests and diseases.

Greater than 10% of trees species that currently comprise urban forests in Minneapolis are found far northward of their natural ranges. This subset of the urban forest canopy may therefore be more amenable to future changes in temperature and precipitation (Woodall et al. 2010). Researchers have examined the possibility for urban forests to act as refugia for natural ecosystems or as northern dispersal centers to facilitate future migration, but ultimately concluded that these potential benefits are unlikely to be realized. This conclusion was due in large part to the physical limitations of urban forests – accounting for few candidate species for migration, having low overall abundance of those suitable species, and being isolated from the surrounding forest matrix.

Considerations Within Particular Ecoregions

This section presents specific considerations of climate change vulnerabilities for the particular ecoregions located within the larger Midwest Region. Where available, information has been organized according to the same "key vulnerabilities" mentioned above, to aid comparing ecoregional specifics to larger regional trends.

Ecological Province 212: Laurentian Mixed Forest

The recent vulnerability assessment by Swanston et al. (2011) includes a list of important vulnerabilities identified for forest ecosystems in northern Wisconsin, which may be generally applied to the ecoregion. This assessment relied on a combination of model results and expert opinion to compile the following list of vulnerabilities. Parenthetical confidence statements reflect the judgment of the authors, based on specific language established by the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change 2005).

- Risk will be greater in *low diversity ecosystems* (very likely).
- Disturbance will destabilize *static ecosystems* (very likely).
- Climate change will exacerbate problems for *species already in decline* (very likely).
- Resilience will be weakened in *fragmented ecosystems* (very likely).
- Altered hydrology will jeopardize *lowland forests* (very likely).
- Changes in habitat will disproportionately affect *boreal species* (virtually certain).
- Further reductions in habitat will impact *threatened, endangered, and rare species* (virtually certain).
- Ecosystem changes will have significant effects on *wildlife* (very likely).

Similarly, this assessment includes a list of characteristics or components that may enable certain species, communities, and ecosystems to better accommodate change (Swanston et al. 2011). More adaptive ecosystems include:

- Species that are currently increasing
- Species with a wider ecological range of tolerances
- Species with greater genetic diversity
- Species and ecosystems adapted to disturbances
- Species and ecosystems adapted to warmer, drier climates
- Species in the middle or northern extent of their range
- Diverse communities and species
- Habitats within larger, contiguous blocks

Laurentian Mixed Forest: Climate change will amplify many ***existing stressors*** *to forest ecosystems (very likely)*

Similar to the trend for the entire Midwest Region, future climate change may amplify existing stressors for forests in the Laurentian Mixed Forest province. A recent example of this synergistic effect is a study from northern hardwood stands recently invaded by exotic earthworms (Larson et al. 2010). Sugar maple trees were more sensitive to drought in invaded stands relative to non-invaded stands, exhibiting more reduced growth during these dry periods. Studies have also highlighted the potential for white-tailed deer (*Odocoileus virginianus*) to alter forest composition due to preferential browsing of seedlings, which can ultimately lead to stand conversion and is a potential multiplier of climate change influences (Salk et al. 2011). Gypsy moth (*Lymantria dispar*) is currently limited by cold winter temperatures across the Midwest Region, and is anticipated to expand its range northward under future climate change scenarios (Vanhanen et al. 2007).

There is already a recognized trend toward less diverse forests in the Laurentian hardwoods, though not necessarily due to changing climate. Schulte et al. (2007) compared early settlement records to contemporary conditions throughout the Laurentian Mixed Forest province and found an overall trend toward reduced forest diversity, reduced forest area, and a greater tendency toward deciduous broadleaf species. They attribute these changes primarily to human land use and persistent herbivory by white-tailed deer. Less diverse systems are generally understood to be more susceptible to increased stresses associated with future climate change (Swanston et al. 2011), which may in turn exacerbate historical trends of decreasing forest land and species diversity.

Laurentian Mixed Forest: Climate change will result in ***ecosystem shifts and conversions*** *(very likely)*

Researchers using LANDIS, a spatially interactive landscape model, across a large region in northeastern Minnesota projected declines in boreal species under both high (A2) and low (B2) emissions scenarios (Ravenscroft et al. 2010). Management treatments that mimicked previous natural disturbance regimes maintained a wider variety of species across the landscape, especially in the low climate change scenario. Under high emissions, however, a much greater proportion of the simulated landscape was converted to non-forested habitats. In general, simulated forest systems across the landscape under both scenarios became more homogenous maple stands (*Acer* spp.) with decreasing proportions of pines (*Pinus* spp.) and hemlock (*Tsuga canadensis*).

Laurentian Mixed Forest: Many tree species will ***not be able to migrate*** *sufficiently to keep pace with climate change (likely)*

Simulations examining forest ecosystem composition and change using LANDIS have reinforced the expectation that forest communities will not be influenced simply by shifts in habitat ranges, but also by species' ability to actually migrate and establish in new areas. For the Boundary Waters Canoe Area in northern Minnesota, Xu, Gertner, and Scheller (2011) found that with increased wind and fire disturbance expected with climate change, forest composition change was influenced more by colonization of new species than competition among existing species. Additionally, LANDIS simulations in northern Wisconsin found that species range expansions and migration are negatively correlated with habitat fragmentation (Scheller and Mladenoff 2008).

This is an important consideration because of the amount of forest that is fragmented in the region. In Minnesota, two major factors contributing to forest fragmentation are large-scale divestiture of forest industry land, and parcelization of non-industrial private forest land (Minnesota Department of Natural Resources 2010. The average landholding size in Minnesota has decreased from 39 acres in 1982 to 31 acres in 2003 (Figure 4), and a similar trend is present in Wisconsin where average parcel size decreased from 41 to 30 acres during 1997 to 2006 (Wisconsin Department of Natural Resources 2010).

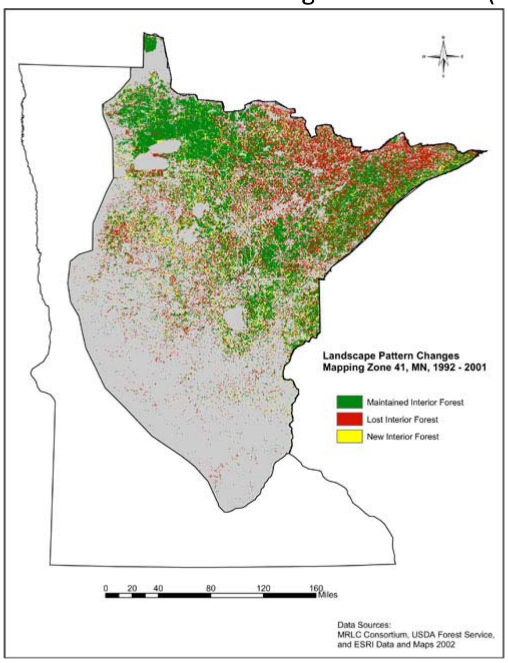


Figure 4: Fragmentation of forest land in Minnesota between 1992-2001 (Minnesota Department of Natural Resources 2010).

Ecological Province 221 & 222: Eastern Broadleaf Forest (Oceanic & Continental)

Eastern Broadleaf Forest: Climate change will amplify many ***existing stressors*** *to forest ecosystems (very likely).*

Climatic changes are likely to cause similar stress on forests in the Eastern Broadleaf province as in the rest of the Midwest Region including drought, tree pests and diseases, non-native species, and altered disturbance regimes. Oak decline is a major stressor throughout the southern half of the Midwest Region. This condition is correlated with drought periods (Dwyer, Cutter, and Wetteroff 1995; Wang, He, and Kabrick 2008; Fan, Kabrick, and Shifley 2006). Species in the red oak group (*Quercus rubra*, *Quercus coccinea*, *Quercus velutina*) are particularly susceptible to decline and make up a large proportion of upland forests in this ecoregion. Decline begins with stressed trees that are then attacked by insects and diseases. If droughts become more frequent or severe, oak decline could worsen. A buildup of fine and course fuels could result from increased tree mortality, increasing the risk of wildfire in the area.

Existing forests may have to compete with undesirable species in warmed conditions. Kudzu (*Pueraria lobata*) is an invasive vine that has devastated forests in the southeastern US. Kudzu's current northern distribution is limited by winter temperatures, occurring nowhere in the Midwest Region except for the southern portion of Missouri. Modeling suggests the risk for kudzu invasion into the Continental and Oceanic Eastern Broadleaf ecoregions could be heightened under future warming (Bradley, Wilcove, and Oppenheimer 2010; Jarnevich and Stohlgren 2009). The aggregate of the models suggests a medium risk for invasion for Missouri, Indiana, Illinois, and Ohio over the next century. Studies have also projected that Chinese/European privet (*Ligustrum sinense; L. vulgare*), highly invasive shrubs, could expand to new territory across the Midwest Region over the next century (Bradley, Wilcove, and Oppenheimer 2010).

Eastern Broadleaf Forest: Climate change will result in ***ecosystem shifts and conversions*** *(likely).*

Forests in the Eastern Broadleaf Forest ecoregion may be at risk of losing keystone species or converting to different ecosystem types. Based on dendrochronological research, white oak (*Quercus alba*) may have reduced growth in the future at the western extent of its range (IL, IA, MO). This is due to a negative correlation between growth and June and July temperatures, which are projected to increase (Goldblum 2010). Decreased habitat suitability for white oak is also projected by species distribution models (Iverson et al. 2008). A decrease in white oak could make way for other species more suited to higher summer temperatures. As mentioned above, a shift in the prairie-forest border could dramatically alter the makeup of ecosystems in the Prairie Parkland and Eastern Broadleaf ecoregions (Frelich and Reich 2010).

Fire was a common disturbance agent within the Broadleaf Forest ecoregions, particularly along grassland transition zones. Fire suppression during the past century has favored shade-tolerant species like maple, while putting fire-adapted tree species like oaks and shortleaf pine at a competitive disadvantage. This trend is illustrated by the large increase in maple species across the Midwest, especially in smaller size classes (Raeker et al. 2010; Illinios Department of Natural Resources 2010; Ohio Department of Natural Resources 2010). This ongoing ecosystem conversion, in combination with existing stressors facing oaks, may make it more difficult for fire-adapted species to expand into available habitat in the future. Lenihan et al. (2008) projected that woodlands and savannahs could occupy a majority of the Eastern Broadleaf Forest province in both high and low future climate scenarios in the absence of extensive fire suppression (Figure 3). If fire-dependent forests continue to decline, forest ecosystems in the southern Midwest may experience unanticipated conversions favoring non-forest or non-native species.

Lowland forest systems in this ecoregion may also be subject to conversions due to climate change. Bald cypress (*Taxodium distichum*) swamps, located in far southern IL, IN, and MO are highly dependent on precipitation and periodic flooding, which are likely to change across the Eastern Broadleaf region based on current climate projections (Middleton 2000; Middleton and Wu 2008). The southern extent of the range is likely the most vulnerable, while the northern extent may serve as a refuge to more southern associated species (Middleton 2006).

Eastern Broadleaf Forest: Many tree species will ***not be able to migrate*** *sufficiently to keep pace with climate change (likely).*
Habitat suitability for shortleaf pine (*Pinus echinata)*, which currently is at its northern extent in southern Missouri, may increase in greater Missouri, southern Illinois, and Indiana (Iverson et al. 2008). However, habitat fragmentation and past management that favored oaks instead of pine could hamper the migration of shortleaf pine into newly suitable areas.

Bald cypress also presents an example of migration barriers that may prevent species from successfully tracking changes in temperature and precipitation. Seeds of bald cypress disperse by water, and most of the watersheds where they are located flow southward (Middleton and McKee 2004). In addition, bald cypress swamps have become increasingly fragmented in the north as they have been drained to make use for agriculture and local rivers have been dammed, making dispersal even more difficult (Middleton and Wu 2008).

Ecological Province 251: Prairie Parkland (Temperate)

Prairie Parkland: Many tree species will ***not be able to migrate*** *sufficiently to keep pace with climate change (likely).*

Fragmentation and parcelization of forest ecosystems is perhaps more drastic in the Prairie Parkland than other ecoregions throughout the Midwest. For example, over 90% of forestland in Iowa is currently divided into private holdings averaging less than 17 acres (Flickinger 2010). Combined with extensive conversion of available land to agricultural monocultures, this ecoregion currently exists as a highly fragmented landscape for forest ecosystems. This condition raises the possibility that tree species in the Prairie Parkland ecoregion may be unable to migrate successfully to future suitable habitat, perhaps more so than other ecoregions in the Midwest.

Benefits from Forests

This section presents information on "key vulnerabilities" that are related to major ecosystem services provided by forest ecosystems. This information in the following sections is relevant across the Midwest Region, therefore we do not provide additional ecoregion-specific context.

Forest Products

5. ***Key Vulnerability: Forest ecosystems will be less able to provide a consistent supply of some forest products (likely).***

One of the benefits humans derive from forests is a diverse supply of wood products. Although the importance of forest industry to the overall economy varies throughout the Midwest Region, it is generally a minor sector of the economy, accounting for between 0.5-2.1% of total employment in a given state and 0.9% of employment across the region (Table 1). The Midwest is, however, an important component of the nation's forest products industry. Wisconsin is the top-ranking paper producer in the country, and Indiana is a national leader in the production of wood office furniture, kitchen cabinets, and other products (Wisconsin Department of Natural Resources 2010; Indiana Department of Natural Resources 2010). The forest products industry is the 4th largest manufacturing industry in the state of Minnesota (Minnesota Department of Natural Resources 2010). While employment related to direct growth and harvest operations has remained more or less consistent, employment in processing mills and manufacturing facilities has been declining steadily (Figure 5).

	Total Private Employment	Timber Employment	Economic Output of Forest Industry
Midwest	23,830,646	215,526	$55.8 billion
Illinois	5,120,970	26,416	$2.5 billion
Indiana	2,449,980	28,069	$7.5 billion
Iowa	1,283,769	14,031	$3 billion
Michigan	3,383,615	23,478	$8 billion
Minnesota	2,417,174	25,505	$6 billion
Missouri	2,358,706	16,356	$5.7 billion
Ohio	4,460,553	31,527	$2.6 billion
Wisconsin	2,355,879	50,144	$20.5 billion

Table 1: Total employment, timber-related employment, and economic output for the forestry sector for the entire Midwest Region and the individual states. Employment figures are from Headwaters Economics (2011). Economic output figures are from the 2010 State Forest Resources Assessments (Flickinger 2010; Minnesota Department of Natural Resources 2010; Price 2008; Wisconsin Department of Natural Resources 2010; Raeker et al. 2010; Illinios Department of Natural Resources 2010; Indiana Department of Natural Resources 2010; Ohio Department of Natural Resources 2010).

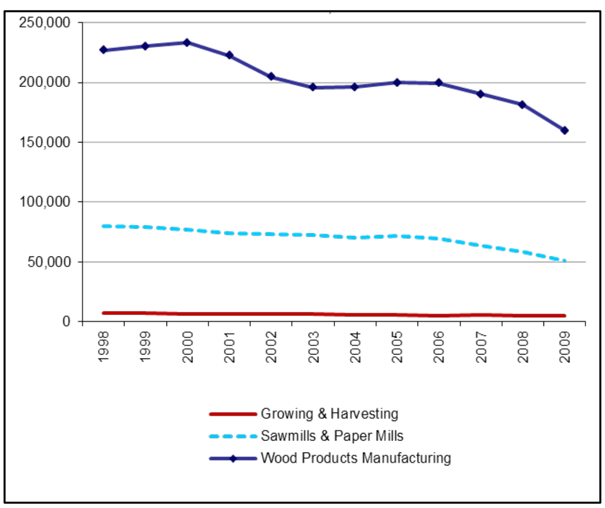


Figure 5: Employment in Timber-related fields, from recent census data compiled across all 8 states in the Midwest NCA region (Headwaters Economics 2011).

The ecological changes that occur as a consequence of climate change could have cascading effects throughout the forest products industry, from altered timber supply to the management practices that may be employed (Irland et al. 2001). These effects depend not only on ecological responses to the changing climate, but also on socioeconomic factors that will undoubtedly continue to change over the coming century. Major socioeconomic factors include national and regional economic policies, demand for wood products, and competing values for forestland (Irland et al. 2001). It is possible that the net benefit of climate change to the forest products industry will be positive, if the industry can adapt effectively.

An example of how climate change may influence the forest products industry throughout the Midwest can be seen in white oak, which occurs in across the grassland and broadleaf forest ecoregions within the Midwest. White oak is an important tree species, economically and ecologically. As recently as 2005, oak species accounted for 36% of annual harvest in Illinois, and white oak in particular was a favored harvest species (Illinios Department of Natural Resources 2010). Oak species are also the primary harvest species in the Ohio portion of the Oceanic Eastern Broadleaf ecoregion (Ohio Department of Natural Resources 2010). The ongoing decrease in oak species is likely a result of several factors, ranging from fire suppression to drought to pests and diseases, as mentioned above. Climate change may amplify the rate of this decrease. The species does show variation in sensitivity to climate parameters across its entire range, highlighting the fact that relationships may differ geographically for widely distributed species (Goldblum 2010).

Future models considering climate change also project that other commercial species like aspen, maples, black cherry, and hickory may see substantial changes in distribution and abundance (Iverson et al. 2008). Large potential shifts in commercial species availability may pose risks for the forest products sector if the shifts are rapid and the industry is unprepared. These trends will be important to examine for other economically important species, and the forest industry will benefit from awareness of regional differences as well as potential opportunities as new merchantable species gain suitable habitat in the region.

Water Resources

6. ***Key Vulnerability*: Many forested watersheds will be less able to produce reliable supplies of clean water (likely).**

Forested watersheds play a vital role in providing clean water supplies. Forest ecosystems reduce surface runoff, soil erosion, water temperatures, and pollutant levels as water moves through the ecosystem (Furniss et al. 2010). Drinking water often arises from forested landscapes, and the proportion of forest cover in source watersheds is inversely related to the cost of water treatment (Ernst, Hopper, and Summers 2004). Protecting drinking water sources remains a much cheaper and effective option than disinfection and filtration of water supplies. As noted in the Indiana Statewide Forest Assessment, forest cover alone cannot ensure water quality, because other factors like storm water management, point-source pollution, and agricultural practices often have large influences (Indiana Department of Natural Resources 2010). Responsible stewardship of forest land is still a critical determinant of overall watershed health, however.

All eight states in the Midwest Region have experienced sharp declines in the ratio of forest acres per person over the past century, with Illinois, Indiana, Iowa and Ohio all having less than one forest acre per person (Barnes et al. 2009). Public surface water supplies are common in all states throughout the Midwest, with the exception of Wisconsin. In Iowa, forests account for only 14% of the land cover in surface water protection zones for municipalities that rely on surface drinking water supplies (Flickinger 2010). The Missouri Department of Natural Resources estimates only 55% of the potentially forested riparian buffers are currently forested across the state (Raeker et al. 2010). If these rates continue to decline, municipal water supplies will be further stressed to provide clean water.

Barnes et al. (2009) developed an index to characterize a watershed's ability to produce clean water by combining six layers of spatial data: the percentage of forest land, agricultural land, riparian forest cover, road density, soil erodibility, and housing density. Much of the Laurentian Forest Province scored very high according to this assessment, while other ecoregions within the Midwest had low to mid-range scores (Figure 6).

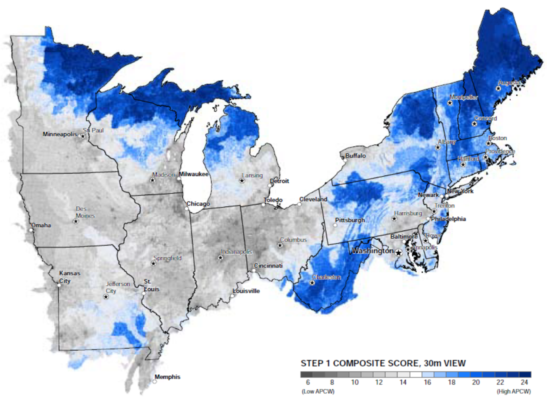


Figure 6: *Index of the Ability to Produce Clean Water, from Barnes et al. (2009). Areas with higher scores have greater ability to produce clean water.*

As outlined above, interacting effects of climate change, habitat fragmentation, disturbance, and forest stressors may result in reduced forest cover throughout the Midwest Region. This could occur through a variety of pathways, including ecosystem shifts and migration of the prairie-forest border, or situations where existing forest species experience declines and new migrants are unable to fully colonize the available habitat. The impacts of climate change on the extent and condition of forest ecosystems across the Midwest Region will alter the ability of these watersheds to produce clean water, which in turn will dictate how municipalities across the region provide water to the human population.

Additionally, regional changes in the quantity and timing of precipitation will further alter the supply of water delivered from forest ecosystems. Across the central United States, the ratio of wintertime snowfall to precipitation has been declining over the past half century (Feng and Hu 2007). This trend has implications for the hydrologic cycle, meaning that a greater percentage of water is delivered through immediate surface runoff rather than through gradual release from snow packs. Cherkauer and Sinha (2010) project that this trend will continue, with increasing surface flows in spring and summer months by the late 21st century in the 4 states surrounding Lake Michigan.

Carbon Storage

7. ***Key Vulnerability*: Carbon storage in many forest ecosystems will be reduced, primarily due to episodic events and through interactions between climate and multiple stressors (possible).**

Forest ecosystems and urban forests play a valuable role as a carbon sink across the Midwest Region (Minnesota Department of Natural Resources 2010; Wisconsin Department of Natural Resources 2010; Raeker et al. 2010; Flickinger 2010; Price 2008; Nowak and Crane 2002; Ohio Department of Natural Resources 2010). Carbon sequestration and storage in forest ecosystems depends on the health and function of those ecosystems in addition to human management, episodic disturbances, and forest stressors. All of these factors will interact with the changing climate, but the effect on carbon storage will vary from place to place. It is possible that forest carbon stocks in localized areas will experience decreases over time under future climate change, but it is also possible that carbon stocks in some areas will increase under climate change. A large-scale decline in carbon stocks across the entire Midwest Region is unlikely.

Each year, forests and forest products nationwide remove greenhouse gases from the atmosphere that are equivalent to more than ten percent of annual US fossil fuel emissions (Smith and Heath 2004; Birdsey et al. 2006; Ryan et al. 2010; McKinley et al. 2011). The accumulated terrestrial carbon pool within forest soils, belowground biomass, dead wood, aboveground live biomass, and litter represents an enormous store of carbon (Birdsey, Pregitzer, and Lucier 2006). Widespread land-use change in the Midwest has dramatically reduced above-ground carbon storage and re-arranged the distribution of carbon pools on the landscape (Rhemtulla, Mladenoff, and Clayton 2009). Terrestrial carbon stocks in the region have generally been increasing for the past few decades, and there is increased attention on the potential to manage forests to maximize and maintain this carbon pool (Malmsheimer et al. 2011; Flickinger 2010; Minnesota Department of Natural Resources 2010). The amount of carbon stored in future forests in the Midwest will be determined in large part by their extent and composition, which already varies considerably across the region. For example, in Wisconsin maple/beech/birch forests sequester an average of 224 metric tons C/acre, while spruce/fir forests sequester an average of 87 metric tons C/acre (Wisconsin Department of Natural Resources 2010). Similarly, the average carbon density in urban forests is about half that of forested ecosystems (25.1 tons C/ha compared to 53.5 tons C/ha, respectively) (Nowak and Crane 2002). Climate change and management are very likely to continue to influence the distribution and composition of forests throughout the region.

Episodic disturbances

Interactions of climate change with wildfires, wind storms, and insect outbreaks may result in net gains or losses of ecosystem carbon. An ecosystem model study by Lenihan et al. (2008), found that more frequent wildfires and ecosystem conversions resulted in average carbon losses of 11% across the eastern US. Continued fire suppression reduced the average carbon loss to 6%. Some studies have shown that repeated disturbances (clear-cut harvesting and fire) reduced annual carbon storage and forest productivity, and have projected that these trends may be amplified by climate change (Gough et al. 2008). Other studies have projected that aboveground live biomass will increase under high and low climate future scenarios, regardless of whether harvesting and wind disturbance are included in the simulations (Scheller and Mladenoff 2005). The trend of increased total biomass projected by Scheller and Mladenoff (2005) occurred despite the fact that many boreal species were extirpated from the study area in their model simulations.

Additionally, insect pests and diseases can determine whether forest ecosystems are net sinks or sources of carbon (Hicke et al. 2011). Forest ecosystems can take decades to recover from widespread pest attacks. If climate change increases the prevalence or activity of these or other disturbance agents, forests in the Midwest could suffer widespread declines in growth or increased mortality.

Effects on productivity

Several studies have projected the outcome of climate change on forest growth and productivity, which could have positive and negative consequences for forest carbon sequestration. Free-air CO_2 enrichment (FACE) experiments in forest stands across several regions have found a consistent increase in net primary production, and suggest that forests may be more responsive to elevated CO_2 than other ecosystem types (Norby et al. 2005; Ainsworth and Long 2005). Ainsworth and Long (2005) estimated a 28% increase in dry matter production in four forest types in response to elevated CO_2, including aspen in northern Wisconsin.

Considering species range shifts due to climate change, Chiang et al. (2008) estimated an increase in net primary production (NPP) in northern Wisconsin, with minimal changes in Ohio. Increases in northern areas of the Midwest may result from greater growth from oak and cherry (*Prunus spp.*) species, which could offset reduced growth in aspen and birch.

Retrospective studies that measure the influences of temperature and precipitation on NPP are rare. Bradford (2011) examined the strength and seasonality of this relationship across the entire Laurentian Forest Province, using two decades of gathered data. The findings from this study indicate that there are multi-year and seasonal controls that govern growth in a given growing season. The weather conditions of a given year are often not directly correlated with the growth during that growing season.

Recreational Opportunities

8. ***Key Vulnerability*: Many contemporary and iconic forms of recreation within forest ecosystems will change in extent and timing (very likely).**

Forest ecosystems are one of the centerpieces of recreation in the Midwest Region. People throughout this region enjoy hunting; fishing; camping; wildlife watching; and exploring trails on foot, bicycles, skis, snowshoes, horseback, and off-highway vehicles (OHV), among many other recreational pursuits. Estimates of actual participation in these activities rely on varying methods and are often limited to fee-based recreation areas, but the popularity of these types of activities reinforces the notion that forests are an important setting for enjoyment of nature.

There are 10 National Forests, 3 National Parks, 4 National Lakeshores, 64 National Wildlife Refuges, and hundreds of state and county parks within the Midwest Region, all of which are major hotspots of forest based recreation and tourism. For the 10 National Forests in the Midwest Region, over 55% of visitors reported travelling more than 50 miles to visit, reflecting the potential of these locations to draw visitors from a wide area (US Forest Service 2011). According to data from 2005-2009, there are approximately 10.6 million visits to the National Forests each year (data reported for different Forests in different years). Total spending associated with these visits was over $700 million.

The state of Wisconsin estimated that forest-based recreationists spend approximately $2.5 billion within Wisconsin communities (Marcouiller and Mace, 1999). Surveys in Wisconsin also show that most types of recreation show stable or increasing demand in future projections (Wisconsin Department of Natural Resources 2010). The state of Ohio found that 62% of the state's recreational sites were located within or nearby forests (Ohio Department of Natural Resources 2010).

Irland et al. (2001) describes the difficulties associated with projecting the impacts of climate change on the recreation industry. Forest-based recreation and tourism are strongly seasonal, and it is unclear if there are particular thresholds for change that will reduce enjoyment of a given activity. Climate change generally stands to reduce opportunities for winter recreation in the Midwest, while warm-weather forms of nature-based recreation may benefit (Dawson and Scott 2010; Jones and Scott 2006; Mcboyle, Scott, and Jones 2007). But scientific literature assessing these impacts is lacking, with the majority of published studies focused on the downhill skiing industry or international tourism (Nickerson, Becerra, and Zumstein 2011).

Saunders et al. (2011) provide a case study for the Midwest Region, focusing on four National Lakeshores and one National Park surrounding the Great Lakes. Total visitor attendance at these five sites is over 4 million people per year, with visitor spending over $200 million. The more immediate impacts of climate change - projected ecosystem disruption, loss of wildlife and fish, changing temperatures, disease outbreaks, and wildfire – could lead to a loss of visitor enjoyment and a drop in visitation at the region's parks.

In the National Visitor Use Monitoring program for National Forests, survey respondents were asked to choose among a few general "substitute behavior" choices, which might serve as general indicators of what the typical response might be to a situation where visiting a given recreational location at a given time was undesirable (US Forest Service 2011). Fewer than half reported their preference would be to travel elsewhere for the same activity, while nearly 20% would have stayed at home or gone to work. Only 35% of visitors reported that they would be willing to travel more than 100 miles to an alternate location. If visitors are seeking a particular type of recreational experience that is shaped in large part by the well-being of the surrounding ecosystem or certain climatic factors, this extent of travel might be more necessary in the future.

The loss of visitor enjoyment, uncertainty about ideal timing of visitation, and increased travel distances could lead to reduced public interaction with a wide range of natural areas, from county parks to National Forests. Such reductions would likely be associated with a decrease in visitor spending. New opportunities could offset decreases on a regional basis, though localized areas may experience decreases in traditional recreational enjoyment and spending.

Cultural Values

9. ***Key Vulnerability*: Traditional and modern cultural connections to forest ecosystems will be altered (likely).**

Some of humankind's more fundamental and yet intangible connections with the environment are the relationships we hold with nature through particular plant and animal species, modes of interaction with the landscape, and special places. These relationships define culture, and they are not always straightforward to assess or interpret. However subtle these cultural relationships to forest ecosystems may be, they are likely to be transformed by climate change. Below, we present some of these potential cultural connections that may be at risk due to climate change.

Forest species

Particular species can hold unique cultural importance, often based on established uses. Changes in forest composition and extent may alter the presence or availability of culturally important species throughout the Midwest Region. For example, Dickmann and Leefers (2003) compiled a list of over 50 tree species from Michigan that were used by several Native American tribes in the region. Among these, white cedar and paper birch stand out as having particular importance for defining a culture and way of life. Unfortunately, these two species are expected to experience large declines in suitable habitat over the next century, due to climate change (Iverson et al. 2008).

Non-Timber Forest Products
Non-timber forest products (NTFPs) are important cultural features and sources of income throughout the Midwest. Some of these include mushrooms, berries, maple syrup, wild ginseng, balsam fir boughs, and Christmas trees. In some cases, NTFPs support regionally important industries based on the harvest and sale of these goods. Collection of balsam fir boughs in northern Minnesota resulted in $23 million in sales for Christmas wreaths (Minnesota Department of Natural Resources 2010). Balsam bough collection on National Forest and State-owned lands drives a $50 million per year industry in Wisconsin (Wisconsin Department of Natural Resources 2010). From 1992 to 2010, the maple syrup industry produced an average of $2.4 million in Ohio, $2.6 million in Michigan, and $2.9 million in Wisconsin (USDA Economic Research Service 2012). Data were unavailable for Minnesota, which is also a large syrup-producing state. Collection of these NTFPs may be influenced by future changes in climate.

Special Places
It may be one of the more difficult cultural connections to firmly document, but association with particular places on the landscape is an important aspect of humankind's relationship with forests. Saunders et al. (2011) provide a few useful examples of how climate change may physically alter the places that we hold dear. Erosion from rising lake levels and storm surges in the Great Lakes has already begun to wash away cultural sites within the Grand Portage National Monument and Apostle Islands National Lakeshore.

Adaptation

Adaptation is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (Parry, Canziani, and Palutikof 2007). Numerous actions can be taken to enhance the ability of ecosystems to adapt to climate change and its effects. People will have a key role in dictating these responses, which might focus on avoiding loss of forest cover, or maintaining forest productivity, or preserving ecosystem processes. Importantly, adaptation measures can also be targeted to address the environmental benefits that forests provide to people, such as water, recreation, and wood products. There is no single "silver bullet" approach to climate change adaptation, but rather a broad array of strategies and approaches that can be tailored to specific ecosystems and management goals. In many instances, targeted policy measures will be necessary to implement adaptation efforts. This section presents general adaptation measures that may be appropriate for the topic areas mentioned earlier, summarized for the entire Midwest Region.

Forest Ecosystems

There is a growing library of tools and resources pertinent to climate change adaptation in forest ecosystems (Glick et al. 2011; Heller and Zavaleta 2009; Millar, Stephenson, and Stephens 2007; Ogden and Innes 2008). Published studies evaluating adaptation methods are lacking, as is long-term monitoring on pilot projects. Nevertheless, this body of knowledge provides a framework for integrating knowledge of projected climate change impacts into natural resource planning and management. There has been an early focus on "no regrets" decision-making and adopting a triage mentality to prioritizing climate change adaptation (Millar, Stephenson, and Stephens 2007). Millar and others also frame the three fundamental options for adapting to climate change as "resistance, resilience, or response" (see box).

Particular land owners or forest management entities may prefer one mode of adaptation over another, or they may have to favor a particular course of action by default. For example, National Wildlife Refuges and other management units with particular mandates to preserve habitat for endangered species might automatically favor "resistance" or "resilience" options for climate change adaptation. Many other landowners, including private landowners, will be able to consider a variety of options and design specific management tactics that are suited for their individual goals.

--------------------------BOX from Swanston and Janowiak (In press) --

The concepts of resistance, resilience, and response serve as the fundamental options for managers to consider when responding to climate change (Millar, Stephenson, and Stephens 2007):

- ***Resistance*** actions improve the forest's defenses against anticipated changes or directly defend the forest against disturbance in order to maintain relatively unchanged conditions. Although this option may be effective in the short term, it is likely that resistance options will require greater resources and effort in resisting change over the long term as the climate shifts further from historical norms. Additionally, as the ecosystem persists into an unsuitable climate, the risk that the ecosystem will undergo irreversible change (such as through a severe disturbance) increases over time.

- ***Resilience*** actions accommodate some degree of change, but encourage a return to prior conditions after a disturbance, either naturally or through management. Resilience actions may also be best suited to short-term efforts, high-value resources, or areas that are well buffered from climate change impacts. Like the resistance option, this option may engender an increasing level of risk over time if an ecosystem becomes increasingly ill-suited to the altered climate.

- ***Response*** actions intentionally accommodate change and enable ecosystems to adaptively respond to changing and new conditions. A wide range of actions exists under this option, all working to influence the ways in which ecosystems adapt to future conditions, instead of being caught off-guard by rapid and catastrophic changes.

Forest Adaptation Resources: Climate change tools and approaches for land managers describes a framework for responding to climate change and is broadly applicable for forest managers across the Midwest Region (Swanston and Janowiak In press). This system creates and gathers scientific information, establishes cross-ownership partnerships, and fosters collaboration between scientists and land managers. The document provides a wide-ranging "menu" of adaptation strategies and approaches and a "workbook" process to help land managers consider ecosystem vulnerabilities, select adaptation approaches that meet their needs, and devise tactics for implementing them. Table 2 highlights the overarching adaptation strategies, which are subsequently tailored to more specific local approaches and tactics.

Strategy	Resistance	Resilience	Response
1. Sustain fundamental ecological functions.	X	X	X
2. Reduce the impact of existing biological stressors.	X	X	X
3. Protect forests from severe fire and wind disturbance.	X	X	
4. Maintain or create refugia.	X		
5. Maintain and enhance species and structural diversity.	X	X	
6. Increase ecosystem redundancy across the landscape.		X	X
7. Promote landscape connectivity.		X	X
8. Enhance genetic diversity.		X	X
9. Facilitate community adjustments through species transitions.			X
10. Plan for and respond to disturbance.			X

Table 2: Climate change adaptation strategies for forest management (Butler et al. In press).

It is important to note the role that forest management can play in the context of climate change adaptation. LANDIS simulations have shown that harvesting can create opportunities to encourage diversity and maintain vulnerable tree species over time, but harvesting can also reduce seed sources and limit regrowth (Scheller and Mladenoff 2005). Studies in Minnesota reveal similar patterns (Ravenscroft et al. 2010).

Urban Forests

A case study from Philadelphia, while outside the region, provides an illustrative example of how cities are evaluating the potential impacts of climate change on urban forests in order to develop appropriate adaptation strategies (Yang 2009). They found that the combined climate stress, pests, and diseases reduced the suitability of 10 tree species commonly planted in the city, although they were able to identify a few species that would be expected to thrive under future conditions. Conducting these sorts of analyses will be necessary for urban forest managers and city planners to effectively plan for change. Chicago's Climate Change Action Plan includes a section on Adaptation, which covers strategies for maintaining and enhancing green spaces and urban forests in the city (Coffee et al. 2010). The Arbor Day Foundation's Tree City USA program, or similar national assistance programs, may offer an effective platform for engaging municipalities across the Midwest Region and sharing best practices for adaptation. As of July 2011, over 1,000 cities and towns across the 8-state region are already participating members in the Tree City USA program (www.arborday.org/programs/treeCityUSA/index.cfm).

Forest Products

The forest products industry has undergone a great deal of change over the past century – technology is continually improving, markets are global, and the policy environment has become more complex. The forest resource base upon which the industry has depended has also been dramatically altered - first as a result of early forest industry practices and subsequent disturbance, and more recently as forests have matured and the landscape has become more fragmented.

Climate change may result in new unpredictable changes for forest ecosystems in the Midwest Region, and the forest industry will benefit most strongly as an economic sector if it continues to respond proactively to landscape changes. The entire industry – from harvest operations to manufacturing – can be actively engaged in an adaptation mindset. This will involve continually incorporating new information on climate change impacts and making calculated responses to manage risk. Species declines or migrations will affect market supplies in different regions of the country, as will climate-induced disturbance events. The timing of harvest and transport operations may also be influenced by temperature and precipitation patterns, which could have cascading impacts throughout the supply chain. New opportunities may appear if climate change has favorable influences on growth rates or results in increased habitat suitability for southern merchantable species.

A critical consideration is that the forest industry will have a vital role in sustaining healthy forest ecosystems. A planned, measured approach to climate change adaptation might ultimately depend on having a vibrant forest industry, because it will require considerable management intervention to actively influence the course of ecosystem adaptation and avoid catastrophic, unplanned outcomes. Forest managers will need to be prepared to encourage resilience or facilitate ecosystem transitions through management operations; an agile industry can take advantage of these management opportunities to produce desired goods and services.

Water Resources

Adaptation of forest ecosystems to global climate change will be essential for preserving the quality of water supplies throughout the Midwest. In a review of the relationship between climate change impacts, forests, and water resources, Furniss and colleagues outline several adaptation guidelines to improve watershed resilience (Furniss et al. 2010). Table 3 summarizes some of these key ideas. Improving the state of knowledge and sharing information widely will help reduce the uncertainty surrounding future projections of water resources. Integrating an understanding of climate change and forest ecosystems into watershed planning will also be essential for systematically addressing these challenges. The authors also advocate a "collaborative, participatory approach to adaptation based on connecting people, their lifestyles, and land-use decisions to their effects on critical watershed services," and outline several strategies for achieving this comprehensive goal. Land management actions across several domains – fire and fuels, wildlife habitat, timber harvest, infrastructure, and habitat restoration – can be implemented with an eye toward maintaining or enhancing watershed function.

- Collaborate to protect and restore watersheds
    - Connect water users and watersheds
    - Link to research and adaptive management
    - Engage the community
    - Link water from healthy watersheds to markets
    - Employ new methods that facilitate collaboration
    - Collaborate globally to support sustainable forests
- Implement practices that protect and maintain watershed processes and services
- Restore watershed processes
    - Restore streams and valley bottoms
    - Restore riparian areas and bottomlands
    - Restore upslope water conditions
    - Reconnect flood plains and habitats

Table 3: Highlighted recommendations on Collaboration and Action from the Water, Climate Change, and Forests report (Furniss et al. 2010).

Carbon Storage

The past few years have witnessed an increased focus on maintaining and expanding forest carbon stocks, both globally and within the US. While it is evident that forests in the Midwest must be managed to provide a full spectrum of ecosystem services, climate change adaptation decisions will also likely incorporate the desire to prevent forest carbon from being lost to the atmosphere. Indeed, this is one sector of activity where climate change adaptation and mitigation strategies can operate in concert.

Malmsheimer et al. (2011) offer several guiding principles for land managers and policy makers to consider when pursuing effective forest carbon management. They focus on maintaining forests as forests, which may take considerable management intervention and public support if wide-scale ecosystem transitions are favored by climate change. This is especially true for the Midwest Region, which contains a mobile prairie-forest border and competing land-use opportunities for agriculture. In addition, they advocate for market incentives to recognize the climate change mitigation benefits of carbon sequestration in long-lived wood products, product substitution for wood-based materials over carbon-intensive materials, and fuel substitution for biomass over fossil fuels.

Hennigar, MacLean, and Amos-Binks (2008) created an optimization model to evaluate strategies for maximizing forest carbon sequestration over several hundred years. Their approach highlights the different approaches to carbon management that can result, based on whether wood products are counted as a short to medium-term carbon sink. This is a policy decision that will certainly influence carbon management and forest adaptation efforts, and cost-benefit models such as those employed in this study will be valuable tools to explore tradeoffs.

Recreational Opportunities

It will be imperative for municipalities, recreation areas, and the associated recreation and tourism industries to acknowledge likely outcomes of climate change and begin preparing for the future. In the Midwest Region, winter sports that depend on snow cover or lake ice offer a clear illustration of the need to adapt our modes of recreation. It may be possible to shift the dates and locations of particular events to take advantage of more favorable conditions. In some cases, areas may become unsuitable for particular forms of recreation. This may cause economic and cultural hardship for cities and towns that have deep-rooted investments in particular forms of recreation, such as cross-country skiing, snowmobiling, or ice fishing. It is important that organizers and participants alike do not take unnecessary safety risks by continuing to operate solely according to tradition.

Conversely, climate change may also offer new opportunities for expanded recreation in forested areas. Spring and fall seasons may be extended for many forms of outdoor recreation, and planning for change sooner rather than later will ease the transition.

Cultural Values

Cultural connections to forest landscapes throughout the Midwest Region will likely be altered by climate change. It is important to document local uses and local knowledge of forests, both as a means to record incremental changes that occur over time and to preserve these sources of knowledge from being lost. Extensive knowledge of the landscape will be essential for effectively planning localized adaptation tactics for forest ecosystems, and a cultural body of understanding can assist this process. In instances where culturally important plants or animals are at risk of local extinction, people may need to prepare for accessing these species in new places. In some cases, it may be possible to actively encourage and prepare climate refugia or design resistance options to maintain particular ecosystem components in an area.

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Great Lakes Nearshore and Coastal Systems

Scudder D. Mackey, Ph.D.

1. **Great Lakes water levels will generally remain within the natural historical range of water levels with annual means slightly below long term mean water levels. Increased precipitation, storm severity and frequency during winter and spring months, and more drought-like conditions in the summer and early fall have implications for short-term, seasonal, and interannual water level variability and the phenology of organisms that rely on those seasonal and interannual water levels. Increased short-term, seasonal, and interannual water level variability will support and maintain coastal wetland biodiversity and associated fish and wildlife habitats.**

2. **Major winter and spring precipitation events will increase nutrient and sediment loadings into the Great Lakes. Reduced ice cover on large lakes will increase surface water temperatures, increase productivity, initiate longer-term thermal stratification , and increases the probability for low DO events in shallow embayments and other great lakes areas (Lake Erie dead zone). Combined with warmer surface water temperatures, increased loadings may result in more widespread algal and cyanobacterial (Microcystin) blooms.**

3. **Increased storm magnitude and frequency coupled with warmer surface water temperatures will reduce ice cover, increase wave power, and reduce winter ice shore protection which will increase the risk for coastal flooding and result in accelerated beach, shore, and bluff erosion.**

4. **During extended periods of low water levels, shallow-water areas will offer potential habitat for submergent aquatic vegetation and new coastal wetland communities. But exposed lakebed areas may be vulnerable to expansion by *Phragmites australis* or other invasive species.**

5. **Increased surface water temperatures will cause gradual ecotonal shifts in aquatic species distributions from cold-water species to warm-water species in intermediate- to shallow-water nearshore and coastal areas of the Great Lakes.**

Great Lakes Nearshore and Coastal Systems

Scudder D. Mackey, Ph.D.

Introduction

The Great Lakes basin contains more than 20% if the world's surface freshwater supplies and supports a population of more than 30 million people. Most of the population either lives on, or near one the Great Lakes. Coastal margin areas are where socioeconomic, environmental, and Great Lakes interests intersect, and therefore it is important to understand how potential changes in climate may impact coastal margin areas.

Climate stressors on Great Lakes and nearshore coastal systems include: 1) changing water level regimes, 2) changing storm patterns and precipitation, and 3) altered thermal regimes. These stressors have the potential to significantly alter the physical integrity of Great Lakes nearshore and coastal systems, which may affect both environmental and economic interests. The objective of this white paper is to provide a brief overview of each of the climate stressors and to assess how future climate scenarios will impact Great Lakes nearshore and coastal systems. Fundamental to this assessment is the understanding that climate change impacts are primarily physical in nature, i.e. how changes in water level regime; storm frequency and magnitude; precipitation and evaporation; ice cover; and air and surface water temperatures impact nearshore and coastal systems. Climate-induced changes to physical processes will impact not only the physical characteristics of the shoreline, but create vulnerabilities for both environmental and economic interests as well. It is important to identify those vulnerabilities so that appropriate adaptive management actions can be taken.

Great Lakes Water Level Regimes (Water Levels)

Within Great Lakes coastal margin and open water systems, the equivalent of natural flow regime is the natural water-level regime. Great Lakes water-level regimes are controlled by the interaction of two master variables, climate and hydrology. Water levels represent the integrated sum of water inputs and losses from the system – typically expressed by a hydrologic water balance equation – that are driven by climate (long-term and seasonal weather patterns), hydrology and flow regime (surface water, ground water, and connecting channel flows), and water use within the basin (water withdrawals, diversions, and connecting channel flows) (Quinn 2002).

Climatic controls, including precipitation, evapotranspiration, and the frequency, duration, and distribution of major storm events are typically driven by seasonal and longer-term climatic cycles (Quinn 2002; Baedke and Thompson 2000). Long-term and seasonal changes in precipitation and evaporation result in the interannual and seasonal variability of water levels and associated connecting channel flows within, and between, all of the Great Lakes (Derecki 1985; Lenters 2001; Quinn 2002). Seasonal Great Lakes water levels and connecting channel flows are higher in the early summer months and lower in the late winter months.

Also influencing Great Lakes water levels are short-term fluctuations in water level that are caused, in part, by local wind or storm events that perturb the water surface, such as a storm surge or seiche event (a seiche is an oscillatory change in the water level surface due to wind or storm event). These short-term fluctuations typically do not reflect a change in the net basin supply (NBS) or overall water balance of the lake or basin.

A more detailed evaluation of Great Lakes water resources (including water levels) based on GCM and RCM models are presented in a separate NCA whitepaper (Lofgren and Gronewold 2012). The IJC International Upper Great Lakes Study (IUGLS) recently completed a 5-year binational study examining sector impacts related to changes in water level regime resulting from Lake Superior water level regulation. The results of that work are reported in a series of peer-reviewed documents and a Final Report that will be formally released to the International Joint Commission on 31 March 2012.

Results of a detailed hydroclimate analysis performed by the IUGLS study suggests that Great Lakes water levels will generally remain within the natural historical range of water levels with annual means slightly below long term mean water levels. Even though uncertainties are high, this projection is generally supported by a suite of both RCM and GCM models that indicate that evaporative losses from the Greats Lakes will continue to increase due to continuing reductions in winter ice cover. However, these losses will be partially offset by increasing local precipitation in the winter and early spring months suggesting continued long-term variability in Great Lake water levels. These models suggest that water leves will hover near long-term historic means until the end of the century, when more significant reductions in water levels are expected under higher emission scenarios (Hayhoe *et al*. 2010).

The IUGLS study evaluated output of 565 model runs from 23 GCMs compiled by Angel and Kunkel (2010) from the fourth IPCC report (IPCC 2007) and used as input for the GLERL AHPS Great Lakes hydrology model (Lofgren et al. 2002; Croley 2005). The model runs utilized future emission scenarios B1 - relatively low, A1B - moderate, and A2 – high emission scenarios. The high emissions scenario A2 corresponds most closely to recent experience (Angel and Kunkel 2010). Predictions of estimated water level changes at the 5th, 50th, and 95th percentiles for Lakes Michigan-Huron by Angel and Kunkel (2010) are presented in Table 1. Estimated water-level changes for Lakes Erie and Ontario are comparable to those for Lake Michigan-Huron, but water level change estimates for Lake Superior may be somewhat less.

Table 1. Estimated Lake level changes for Lake Michigan-Huron at the 5th, 50th and 95th percentiles

Year	*5th*	*50th*	*95th*
B1 Low Emission Scenario			
2020	-0.60 m	-0.18 m	0.28 m
2050	-0.79	-0.23	0.15
2080	-0.87	-0.25	0.31
A1B Moderate Emission Scenario			
2020	-0.55 m	-0.07 m	0.46 m
2050	-0.91	-0.24	0.40
2080	-1.43	-0.28	0.83
A2 High Emission Scenario			
2020	-0.63 m	-0.18 m	0.20 m
2050	-0.94	-0.23	0.42
2080	-1.81	-0.41	0.88

IUGLS Final Report (IUGLSB 2012), modified from Angel and Kunkel (2010)

By 2050, water levels may be 20 to 25 cm lower than the current long term mean for Lakes Michigan-Huron, Erie, and Ontario and 25 to 40 cm lower by 2080*, but uncertainties associated with emission* *scenarios and the GCM/RCM models are high and the confidence level for future these estimated water level changes is* <u>*low*</u>*.* A major conclusion of the IUGLS study was that "water level changes in the near-term future may not be as extreme as previous studies have predicted. Lake levels are likely to continue to fluctuate, but still remain within a relatively narrow historical range. While lower levels are likely, the possibility of higher levels cannot be dismissed."(IUGLSB 2012)

Changing Storm Patterns and Precipitation

Modelling results attempting to estimate future mean annual precipitation are equivocal and highly variable. A majority of models generally agree that there may be a slight increase in mean annual precipitation ranging from 2 to 7% over the next 30 years, which continues the documented historical trend of increased precipitation in the region (Hayhoe *et al.* 2010). However, there appears to broad agreement between the models that the frequency and magnitude of extreme precipitation events (interpreted to mean severe storms) increases (+30% for A2 scenario, +20% for B1 scenario) during the winter and spring months, and is less during the summer and early fall months. Increased precipitation and storm severity (and frequency) during winter and spring months and more drought-like conditions in the summer and early fall has implications for short-term, seasonal, and interannual water level regimes and the phenology of organisms that rely on those seasonal and interannual water level cycles.

The confidence level for values of estimated mean annual precipitation is <u>*low*</u>*. The confidence level for extreme precipitation events is* <u>*moderate to low*</u>*, with decreasing certainty toward the end of this century.*

Great Lakes Thermal Regimes

The Great Lakes region could see substantial increases in annual and seasonal air temperatures and extreme heat events, particularly under the A2 (higher emissions) scenario (Wuebbles *et al.* 2010). Over the next few decades (2010–2039), it is anticipated that annual-averaged air temperatures will increase on the order of 0.6–0.8 °C. Near the end of the century (2070–2099), annual-averaged air temperatures could increase by 1.7–2.2 °C under the B1 (lower emissions) scenario , and by 4.5 °C under the A2 (high emissions) scenario. The greatest air temperature increases will occur during the summer months (up to 6 °C or 10 °F). Along with warming temperatures, there will be a timing shift where the last frost date will occur 30 days earlier under the A2 scenario and 20 days earlier under the B1 scenario (Wuebbles *et al*. 2010).

Increasing air temperatures in the Great Lakes region will affect Great Lakes surface water temperatures by reducing the extent and duration of Great Lakes winter ice cover. An empirical temperature model developed by Trumpikas et al. (2009) was used to estimate Great Lakes surface water temperatures for several emission scenarios. For all of the Great Lakes, surface water temperatures are estimated to increase on the order of 1.5 to 3.9°C under the A2 (high emissions) scenario and 1.6 to 3.2°C for the B2 (low emissions scenario) by 2050. At the end of the century, surface water temperatures are expected to increase on the order of 3.3 to 6.7°C for the A2 scenario and 2.4 to 4.6°C for the B2 scenario.

Along with warming surface water temperatures there will also be a timing shift where surface water temperature values will increase earlier in the spring (35 to 47 days earlier) and later in the Fall (26 to 51 days later) under the A2 scenario. Similarly, surface water temperature values will increase 24 to 31 days earlier in the Spring and 18 to 36 days later in the Fall under the B2 scenario. For Lake Superior, and to a lesser extent Lakes Michigan-Huron, summer surface water temperature warming generally exceeds the rate of atmospheric warming due to reduced winter ice cover, which results in an earlier onset of thermal stratification and a longer surface warming period (Austin and Colman 2007). Over time, it is anticipated that thermal stratification will occur earlier in the spring, and later in the fall as surface water temperatures continue to increase.

The estimated surface water temperature values within the next 30 years have a moderate confidence level, and surface water temperature values estimated toward the end of the century have a low confidence level.

Climate Stressors and Great Lakes Coastal Systems

Anticipated long-term changes in climate have the potential to significantly alter the physical integrity of Great Lakes basin (e.g. Lee *et al.* 1996; Kling *et al.* 2003; Mackey *et al.* 2006; Solomon *et al.* 2007; Ciborowski et al. 2008; Wuebbles et al. 2010). Potential climate-change induced alterations due to weather, i.e. precipitation, evapotranspiration, and storm frequency, severity, and patterns will alter the physical and habitat integrity of the Great Lakes basin, including:

- Great Lakes water levels and flow regimes – changing net basin water supplies and water level regimes; increased water level variability (frequency and magnitude); altered coastal circulation patterns and processes; seasonal changes in flooding; loss of hydraulic connectivity; altered coastal margin and nearshore habitat structure;
- Storm Patterns – changing storm magnitude, frequency, and direction; altered littoral sediment transport processes; increased shore erosion; reduced nearshore water quality; reduced marina/harbor/port access (increased dredging activity);
- Precipitation- seasonal alterations in precipitation and flow regimes; spatial and temporal shifts in seasonal timing; altered riverine and floodplain habitat structure and connectivity;
- Thermal regimes - altered open-lake and nearshore surface water temperatures; reduced ice cover; deeper and stronger thermal stratification; spatial and temporal shifts in seasonal timing; and
- Latitudinal shifts in ecoregions – regional changes in land and vegetative cover and associated terrestrial and aquatic communities and habitats (affecting coastal margin areas).

Habitat is the critical component that links biological communities and ecosystems to natural physical processes and the underlying physical characteristics of the basin. The pattern and distribution of habitats are controlled, in part, by interactions between energy, water, and the landscape (e.g., Sly and Busch 1992; Higgins *et al.* 1998; Mackey and Goforth 2005; Mackey 2008). Habitats are created when there is an intersection of a range of physical, chemical, and biological characteristics that meet the life stage requirements of an organism, biological community, or ecosystem (Mackey 2008).

Seasonal changes in water level and flow regimes, thermal structure, and water mass characteristics, interact with the underlying landscape to create repeatable patterns and connections within tributaries, lakes, and shorelines within the basin. The pattern of movement of water, energy, and materials through the system (which depends on connectivity) also exhibits an organizational pattern, persists, and is repeatable. For example, these patterns and connections, in part, control the seasonal usage of Great Lakes fish spawning and nursery habitats (Chubb and Liston 1985). Moreover, high-quality coastal margin habitats (both aquatic and wetland) are created by a unique set of environmental conditions and processes that together meet the life-stage requirements of a species, biological community, or ecological function (Mackey 2008). These processes play a significant role, ultimately determining the distribution and utilization of essential coastal margin habitats within the Great Lakes system.

Vulnerability of Great Lakes Coastal Systems to Climate Change

Tables 3-1 and 3-2 summarize the vulnerability linkages between the climate stressors identified above and the coastal system components described below. The uncertainty associated with each of the components is based on the understanding we have of the interaction (and resulting impacts) between the climate change stressors and each component. The uncertainties provided in these tables do not incorporate the uncertainty associated with the climate change stressor.

Great Lakes coastal margins can be delineated into four major hydrogeomorphic groups, nearshore; beaches, barriers, and dunes; wetlands; and bluffs. These areas are defined by the hydrogeomorphic characteristics of the shoreline and the dominant physical processes that act on those shorelines. Climate change impacts to coastal margins are primarily physical in nature, i.e. changes in water level regime; storm frequency and magnitude; precipitation and evaporation; ice cover; and air and surface water temperatures. Climate-induced changes to physical processes will impact not only the physical characteristics of the shoreline, but create vulnerabilities for coastal habitats, biological communities, and ecosystems that rely on those shorelines as well.

<u>Nearshore areas</u> represent the area encompassed by water depths ranging from 3 to 30 m in all of the Great Lakes except Lake Erie. In Lake Erie, the nearshore is defined by the area encompassed by water depths ranging from 3 to 15 m. Dominant physical processes acting on the nearshore zone include wind-driven coastal circulation patterns; storm generated wave energy; nearshore lakebed sediment transport processes; and nearshore lakebed downcutting. Great Lakes nearshore areas are vulnerable to climate-induced changes in storm magnitude, frequency, and storm direction. Anticipated physical impacts include altered nearshore circulation patterns, erosion and removal of protective sand cover from the lakebed, increased potential for lakebed downcutting, and degradation of nearshore water quality (increase in nearshore turbidity). Nearshore spawning and nursery habitats may be impacted by a coarsening of lakebed substrates and active erosion and sediment transport on the lakebed. The resulting coarse lakebed substrates provide additional habitat for lithophylic invasive species such as dreissenids (zebra and quagga mussels) and the round goby (e.g. Janssen *et al*. 2004; Meadows *et al*. 2005).

<u>Beaches, barriers, and dunes</u> include high energy areas within 0 to 3 m water depths and adjacent low-relief coastal margin, embayed, and back bay areas. Beaches and barriers are created and maintained by littoral sediment transport processes and dune complexes are created by wind-driven sand deflation processes. Dominant physical processes affecting these coastal margin areas include wind and storm generated wave energy; littoral sediment transport processes; and both long- and short-term fluctuations in Great Lakes water levels. Anticipated physical climate impacts include increased littoral sediment transport rates, beach erosion and reduction in beach widths, degradation of nearshore water quality (increase in nearshore turbidity) and thermal effects resulting in the reduction or loss of winter ice cover during the winter months (Assel 2005) and increase in wave energy and loss of winter ice shore protection (USACE 2003).

During periods of high water levels, barrier systems are more vulnerable to major storm events which may result in eventual breaching of the barrier beach. During periods of low water levels, benthic and fish communities are vulnerable to lakeward shifts of the shoreline, which may change the location and distribution of nearshore spawning and nursery habitats in low-relief shallow water areas (Mackey et al. 2006). Moreover, adjacent wetland areas may become hydraulically isolated from adjacent tributary and lake water bodies disconnecting potential spawning and nursery habitats (e.g. Mortsch 1998; Wilcox et al. 2002; Wilcox 2004; Mortsch et al. 2006). Newly created shallow-water areas will offer potential habitat for establishment of submergent aquatic vegetation and coastal wetland communities. But exposed lakebed areas may be vulnerable to the expansion of invasive species such as Phragmites australis (e.g. Tulbure et al. 2007).

In response to historically high water levels in the mid-1980s, extensive coastal engineering works and the resulting loss of littoral sand from adjacent coastal margin and nearshore areas have created habitats that are now much more coarse-grained and heterogeneous than would have naturally been present along many Great Lakes coastlines. It is anticipated that as Great Lakes water levels decline, littoral sand deposits will become stranded at higher shoreline elevations and lost to the active littoral system (M. Chrzastowski, Illinois DNR, pers. communication, 2006). The loss of these sand resources may be significant, especially along sand-poor Great Lakes cohesive shorelines.

One of the consequences of these substrate changes is the rapid colonization and spread of aquatic invasive species (such as *dreissenid* spp.) that have adversely impacted food web-dynamics and the Great Lakes ecosystem. It is only now recognized that many of the physical changes that have occurred in the nearshore zones of the Great Lake have provided the opportunity for massive expansion of these invasive species along with significant associated ecological impacts (e.g. Janssen *et al.* 2004, Meadows *et al.* 2005).

Coastal wetlands are commonly found landward of protective beach-barrier systems, within protected embayments, along open-coast shorelines (i.e. fringing wetlands), and in unaltered (natural) rivermouths. Great Lakes coastal wetlands provide essential habitat for more than 80 species of fish (Jude and Pappas 1992). More than 50 of these species are solely dependent on wetlands, while more than 30 additional species utilize wetlands during a portion of their life history (Jude and Pappas 1992, Wilcox 1995). Other fish species may use wetlands for short periods of time as refugia (predator avoidance) and for forage (food supply). Waterfowl, nesting birds, amphibians, mammals, and reptiles also utilize wetland and coastal margin habitats. Their distribution and abundance are intimately tied to wetland vegetative cover and the hydrogeology of the wetland (e.g. Timmermans 2001; Timmermans *et al.* 2008)

More recent research has documented a relationship between wetland plant zonation (biodiversity) and fish community composition (Uzarski et al. 2005; 2009; Albert *et al*. 2005). Intact coastal wetlands with several plant zones (sustained by water level fluctuations) provide cover, prey, spawning and nursery habitats (Goodyear *et al.* 1982; Jones 1996b; Lane *et al*. 2006a). The high productivity and structural diversity of Great Lakes coastal wetlands are maintained by natural cycles of high and low water levels as well as natural seasonal water level fluctuations (Wilcox 1995; 2004, Albert *et al*. 2005, Keough *et al*. 1999, Mayer *et al.* 2004). On Lake Ontario, water level regulation resulted in range compression and loss of wetland biodiversity, plant community zonation, and ecological functionality (Wilcox *et al.* 2007; Wilcox and Meeker 1991; 1992; 1995; Busch and Lary 1996).

As Great Lakes water levels regimes are expected to remain slightly below the long-term mean, an anticipated increase in short-term, seasonal, and interannual variability of water levels driven by changes in local precipitation and increased storm frequency will benefit Great Lakes wetlands by maintaining and/or restoring plant community zonation, increasing wetland biodiversity, and enhancing environmental benefits. However, increased variability in water level regimes may alter the phenology of wetland-dependent fish communities and other aquatic organisms due to alterations in seasonal timing and duration (Casselman et al. 2002, Kling et al. 2003; Uzarski et al. 2005; 2009)

Coastal bluffs are a dominant shoreline type in the Great Lakes and are created when upland areas are subject to mass-wasting processes initiated by instabilities created by wave erosion at the base of the bluff. These processes have been active along Great Lakes shorelines for thousands of years and have contributed most of the sediments that maintain beaches along Great Lakes shorelines. Physical processes affecting these coastal bluffs areas include the expenditure of wind and storm generated wave energy; littoral sediment transport processes; and both long- and short-term fluctuations in Great Lakes water levels. Anticipated physical climate impacts include increased bluff erosion/recession rates; degradation of nearshore water quality (increase in nearshore turbidity) and thermal effects resulting in the reduction or loss of winter ice cover during the winter months (Assel 2005) and increase in wave energy and loss of winter ice shore protection (USACE 2003).

Erosion of coastal bluffs is episodic and is driven primarily by a combination of wind and storm-driven waves (wave power) expended along Great Lakes shorelines and Great Lakes water levels (e.g. Brown et al. 2005). As Great Lakes water level regimes are expected to remain slightly below the long-term mean, anticipated increases in local precipitation and increased storm magnitude and frequency will increase the cumulative wave power expended along Great Lakes shorelines. The increase in cumulative wave power combined with possible changes in storm direction could significantly alter the rate and direction of littoral sediment transport increasing the exposure of Great Lakes coastal bluffs to wave attack. During periods of high water levels, beaches become narrower reducing the effectiveness of beaches as natural shore protection. Erosion of coastal bluffs and adjacent upland areas increases, with resulting reductions in nearshore water quality. During periods of low water levels, more of the beach face is exposed resulting in wider beaches that provide natural shore protection and may reduce erosion of coastal bluffs and adjacent dune and upland areas (Meadows et al. 2005; Brown et al. 2005). Moreover, the reduction or loss of winter ice cover during the winter months due to anticipated warmer air and surface water temperatures will result in an increase in wave power and loss of winter ice shore protection.

Altered thermal regimes - Anticipated climatic effects include increased surface water temperatures; seasonal timing shifts in thermal structure; stronger thermal stratification; longer duration of thermal stratification, reduced ice cover, and reduced shore winter. Similar changes in large lake thermal structure were observed in several other north temperate deep lakes (Shimoda 2011).

For example, warmer surface water temperatures combined with lower Great Lakes water levels affects the thermal structure of the Great Lakes causing changes in both lake chemistry and lake ecology (Sousounis and Grover 2002). During periods of low water levels, higher surface water temperatures will create a deeper and stronger thermocline that will reduce the water volume in the hypolimnion and result in more frequent episodes of anoxia. In the central basin of Lake Erie, reduced hypolimnion water volumes combined with altered nutrient cycling by invasive zebra/quagga mussels (*Dreissenid* spp.*)* may result in more frequent occurrences of an expanded dead zone" (Lam *et al*. 1987, 2002; Charlton and Milne 2004). As water temperatures increase, dissolved oxygen levels decrease as warm water holds less oxygen than cold water. Moreover, warm waters increase respiration rates for aquatic species further depleting dissolved oxygen levels. Even though the deep northern lakes are relatively immune from low DO levels, shallower water bodies, embayments, and some tributaries may be susceptible to low DO levels as water temperatures increase. Moreover, Warmer water temperatures combined with increased nutrient loads may increase productivity and nutrient recycling, which may stimulate the growth of filamentous blue-green algae (*Cladophora* spp) which has been shown to impact nearshore water quality, habitats, and is an aesthetic problem for coastal property owners and beaches, and may contain pathogens (Hellman *et al.* 2010). As these organisms die and settle to the bottom and decompose, oxygen is consumed reducing DO levels even further.

In Lake Erie, warm surface water temperatures and increased nutrient loads may also result more widespread and frequent Microsystin blooms. Moreover, water temperature increases are positively correlated with mercury methylation rates and increase the availability of methyl mercury for incorporation into fish tissue. Warmer surface water temperatures may facilitate (increase) the rate of mercury contaminant uptake into the food chain that may result in increased levels of mercury contamination in fish (Bodaly *et al*. 1993; Yediler and Jacobs 1995).

The abundance of several species of important recreational and commercial fish (lake trout, walleye, northern pike, and lake whitefish) varies with the amount of thermally suitable habitat (Christie and Regier 1988; Lester *et al*. 2004; Jones *et al.* 2006a). A warm thermal structure may cause a northward shift of boundaries for both warm and cold-water fishes, affecting abundance, distribution, and resilience to exploitation (Minns and Moore 1992; Shuter and Meisner 1992; McCormick and Fahnenstiel 1999; Magnuson *et al.* 1997; Casselman 2002; Brandt 2002; Kling *et al*. 2003; Sharma 2007). Increasing surface water temperatures could also remove existing thermal constraints that have protected the Great Lakes from invasive organisms in the past, and increase the potential number of organisms that can successfully invade the lake (Mandrak 1989). In response to these shifted thermal boundaries, zebra/quagga mussels, round gobies, and other aquatic nuisance species may be able to expand their existing ranges further northward into the upper Great Lakes (GLFC 2005).

Ports and Harbors/Infrastructure – These coastal structures are generally larger than private structures and therefore may have a significant impact on the coastal margin. The structures are typically designed to protect and maintain both commercial and recreational navigation channels and associated infrastructure. Maintenance of these structures is typically a Federal or State responsibility. Depending on use, the navigation channel may be dredged on an annual basis to accommodate large commercial vessels. During high water periods, anticipate impacts are increased risk of coastal flooding during major storm events; increased littoral and riverine sediment transport rates (especially during major storm events); and increased risk of storm damage to the navigation structure. During low water periods, anticipated impacts are increased dredging of navigation channels to maintain design depths; increased littoral sediment transport rates (during major storm events); light-loading of commercial vessels to maintain draft over shallow areas in the navigation channel; and a decrease in the number of available commercial or recreational slips due to low water conditions. An increase in surface water temperatures will reduce winter ice cover and may provide an opportunity to extend the commercial navigation and recreational boating season.

Coastal Property - The effects of climate change in developed coastal areas will be exacerbated by anthropogenic activities, especially in areas where submerged lands may be exposed and development pressures in coastal areas are high. Climate change projections suggest that even though mean water levels will remain near, but slightly lower than long-term mean water levels, there will be increased short-term variability in water levels in response to increased storm magnitude and frequency, especially during the winter and early spring months. During periods of high water, coastal flooding risks are high; risk of shore and beach erosion due to storm derived waves is high; and an increased risk of damage to infrastructure (shore protection structures) and upland property loss during major storm events. During periods of low water, flooding and erosion risks are low. However, during extended periods of low water, property owners tend to “migrate lakeward” by filling shoreline areas for development, installing shore protection, and removing submergent and emergent aquatic vegetation to promote water access and provide a viewshed. These shoreline alterations affect natural coastal processes and the ecosystem, and will have a detrimental affect on Great Lakes nearshore and coastal margin environments. Recent work by Uzarski et al (2009) clearly demonstrated the deleterious effects of vegetation removal on local fish and aquatic plant communities and coastal biodiversity.

An interesting cross-cutting issue is related to the increase in surface water temperatures due to altered thermal regimes. Similar to coastal bluffs, the reduction or loss of winter ice cover during the winter months will result in an increase in cumulative wave power and loss of winter ice shore protection. There will be an increased risk of shore and beach erosion even during periods of low water. Moreover, there will be degradation of nearshore water quality as well.

Discussion

Both global and downscaled regional climate circulation models have been used to predict changes in temperature, weather, precipitation, storm severity and frequency, and indirectly Great Lakes water levels. These predictions have a high degree of uncertainty and represent a range of possible futures or scenarios. For all of these scenarios, the physical integrity of the Great Lakes will be modified or altered in response to changing climate conditions. Thus, ecological responses to climate change will be driven primarily by changes in physical integrity, and these responses may be nonlinear, especially if boundaries and thresholds are exceeded (Burkett *et al*. 2005). Synergistic or cross-cutting interactions between climate stressors may be additive and cause unforeseen environmental or socioeconomic impacts (see examples in Table 2). Moreover, these responses may cascade through the entire system increasing the uncertainty associated with the long-term prediction of coastal margin impacts.

Table 2. Cross-Cutting Issues

Climate Stressor	Condition	Condition	Condition	Impacts
Water Level Regime Thermal Regime Storm Patterns	Low Water Levels	Strong Thermal Stratification	High Winter-Spring Precipitation, (High Nutrient Loads	Low Dissolved Oxygen, Lake Erie Dead Zone
Storm Patterns Water Level Regime Thermal Regime	Increased Wave Power (Storms)	High Water Levels	Reduced Ice Cover, No winter Ice Protection	Shore and Beach Erosion (all seasons)
Thermal Regime Storm Patterns	High Surface Water Temperatures	High Winter-Spring Precipitation, (High Nutrient Loads)		Blue-Green Algal Blooms, Microcystin Blooms in nearshore waters

Examples where multiple climate stressors interact to produce an impact (or benefit). Conditions are listed in the same order as the stressor listing. Multiple conditions can be listed for each stressor.

Recommendations

Additional work is needed to more fully understand the biophysical linkages between physical habitats, associated biological communities, and the natural processes that connect them. Future changes to the ecosystem may yield changes that have not yet been observed and for which data do not exist. It is only through an understanding of biophysical processes that we may be able to predict the ecological responses of the Great Lakes ecosystem due to changes in water-level regime. Moreover, additional tools/models need to be developed that integrate physical and ecological processes to simulate potential changes in environmental conditions and associated aquatic habitats resulting from long-term changes in water-level regime. Using these models, it will be possible to identify potential long-term management, protection, and restoration opportunities based, in part, on an understanding of biophysical processes.

The resulting management, conservation, and protection strategies must be designed to protect potential refugia, transitional, and newly created coastal margin and nearshore habitat areas from anthropogenic modification and/or degradation. As water levels recede, there will be increasing societal pressure to develop and modify newly exposed areas of the shoreline. Critical reaches of the Great Lakes shoreline (as identified by the long-term models) must be protected and preserved to ensure that essential ecological functions are maintained during periods of transition.

It will also be necessary to establish a long-term, aquatic habitat research and monitoring effort within the Great Lakes to track changes and continually update and refine the heuristic models. An important consideration will be to identify the appropriate variables to be monitored and to establish thresholds or triggers that tell us *when* to modify resource management and protection policies. This approach will provide the knowledge and science-based tools to build the capacity of key agencies, organizations, and institutions to identify and implement sustainable protection, restoration, and enhancement opportunities.

This discussion highlights the need to incorporate management and research strategies designed to address uncertainty and respond to potential long-term stressors, such as climate change, water diversions, and continued growth and development which have the potential to impair the physical integrity of the Great Lakes. Given the uncertainties associated with climate change, it is necessary to implement a proactive anticipatory management approach (commonly referred to as adaptive management strategies) that identifies long-term planning, protection, and restoration needs in response to climate-change induced stressors and impairments within the Great Lakes basin. Application of adaptive management strategies will help to ensure the physical and ecological integrity of the Great Lakes in the face of major environmental change.

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National Climate Assessment
Midwest Region, Energy Sector
Climate Change and Energy
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Key messages

Both climate change and climate change policy are intrinsically important to the energy sector. Climate change policies adopted by the states are already affecting planning and investment decisions as utilities respond to new policy requirements and anticipate eventual federal greenhouse gas and other climate and air regulations. The movement away from fossil fuels to renewable but intermittent resources, such as wind and solar, has significant implications for the tradeoffs among goals of clean, reliable, and affordable energy and the respective institutions and agencies responsible for achieving those goals. The Midwest region may be advantaged in terms of relative climate change impacts by its northern latitude and relatively abundant water resources.

1. INTRODUCTION

Both climate change and climate change policy are intrinsically important to the energy sector. The sector bears considerable, yet not exclusive, responsibility for climate change associated with greenhouse gas (GHG) emissions from fossil-fuel-based production facilities, namely electric power plants. Activity within the energy sector can thus be understood in the context of both problem and solution, where the sector's heavy reliance on fossil fuels makes the sector a target of remedial policies at both the state and federal level. Consequently, the pattern of response and adaptation within the sector may be driven as much by climate change policy as by actual and anticipated climate change.

This review, drawing from both the academic and applied literature, focuses on climate and climate change policy with respect to both the supply-side (production) and the demand-side (consumption) of the sector. Federal and state policy developments are summarized. A number of emerging and critical policy issues are also considered.

While climate change will affect the energy sector, the effects of climate change policy are more immediate and potentially more far-reaching. Climate change considerations permeate modern energy policy, along with concerns about energy security, resource renewability, and economic development. Energy providers are subject to increasingly stringent environmental regulations that require significant investment in emissions reduction, alternative energy resources, transmission facilities, and grid modernization. Simultaneously, aging infrastructure and emerging capacity requirements are adding to cost pressures. Efficiency gains from standards, conservation programs, and load-management tools will help offset some costs. Even so, utility ratepayers can be expected to bear the cumulative burden of infrastructure investments and environmental mandates as the controversy over costs and their allocation is inevitable.

Structure and Regulation of the Energy Sector

Public utility companies that provide energy services comprise a significant share of the U.S. economy in terms of gross domestic product and employment (Beecher, 2012c) . Utility expenditures also constitute a significant share of household expenditures. Over the last decade, the average percentage change in Consumer Price Index for electricity was approximately 4%, although this rate of change is less than the change for the entire index (Beecher, 2012b).

Publicly and privately owned utilities are subject to federal and state environmental regulation under the Federal Clean Air Act (CAA) overseen by the U.S. Environmental Protection Agency (EPA) and also implemented through state environmental agencies. Each state also maintains a public service commission that oversees the economic regulation of utilities.

Most energy utilities are privately owned and subject to economic regulation by the Federal Energy Regulatory Commission (FERC) and state public utility commissions. Over the last two decades, energy markets have been substantially restructured, which, in turn, affects how they are regulated. The natural gas industry was first to be restructured in the 1980s to deregulate wellhead production and separate it from interstate pipeline transmission and local distribution. The electricity industry has been only partially restructured and oversight varies by state (U.S. Energy Information Administration, 2010). In Illinois and Ohio, regulatory responsibility is divided across generation, transmission, and distribution functions; in Michigan, transmission was separated but generation and distribution remain under integrated companies. Utilities remain vertically integrated in other Midwest states (Indiana, Iowa, Minnesota, Missouri, and Wisconsin). Both federal authority for interstate wholesale power markets and restructuring have the effect of limiting state jurisdiction for the sector to intrastate markets and retail distribution.

Much federal regulation focuses on wholesale operations while retail oversight belongs to the states. The prices and profits of vertically integrated and distribution utilities are regulated because they are organized as state-sanctioned monopolies. Various technical and economic characteristics distinguish utilities from other enterprises and contribute to their monopolistic character. Economic regulation is designed to prevent abuse of monopoly power while balancing the interests of utility investors and ratepayers. Regulators review the prudence of utility investments and expenditures in a quasi-judicial process prior to their inclusion in rates. Rate-making, or the determination and allocation of a utility's revenue requirements, is controversial, particularly in the contemporary context of rising costs.

In addition to environmental and economic regulation, energy utilities are subject to considerable financial regulation (by the Securities and Exchange Commission), accounting rules (by the Federal Accounting Standards Board), and reliability standards (by the North American Electric Reliability Corporation). Bulk power transmission for various regions is managed by independent system operators such as MISO (Midwest) and PJM (Pennsylvania New Jersey Maryland), which impose planning and operational requirements on market participants. As a result of extensive oversight, the sector is considered relatively accountable and transparent.

Energy Profile for the Midwest

The Midwest region is home to numerous powerplants (Exhibit 1) and continues to rely heavily on coal for generating electricity (Exhibit 2). The power production fleet is aging and much of the recent capital investment has been in peaking facilities as compared to baseload capacity. Between 2000 and 2010, a small shift can be detected toward natural gas and wind energy, attributable to favorable natural gas prices and support for renewable energy development. Among states in the region, Illinois is highest in both production and sales of electricity (Exhibit 3).

Growth in retail electricity sales in the Midwest began to slow prior to the recent recession (Exhibit 4). Trends in population and economic activity, as well efficiency gains, are likely related and will continue to shape demand (Exhibit 4). Recessionary influences on energy demand are apparent. Higher prices, particularly for peak periods of usage, have and will continue to influence demand and its timing. Electricity prices in the region are comparable or below the national average (Exhibit 5), reflecting the cost of infrastructure, resources, and, increasingly, environmental mandates.

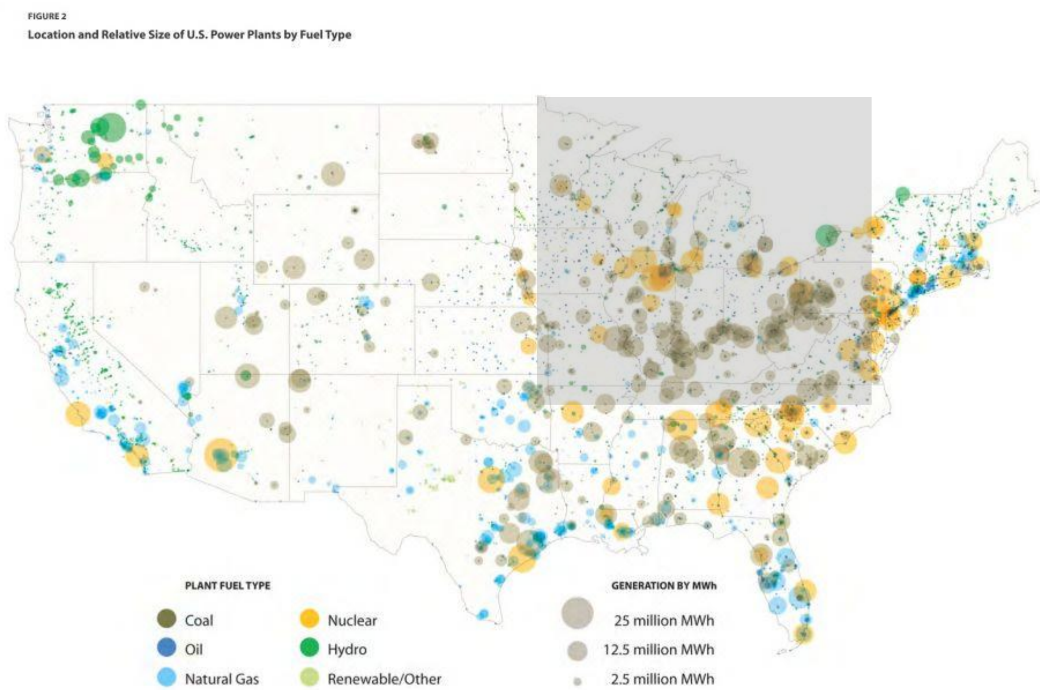

Exhibit 1. Electricity power plants in the United States and Midwest region.
Source: Ceres (2010).

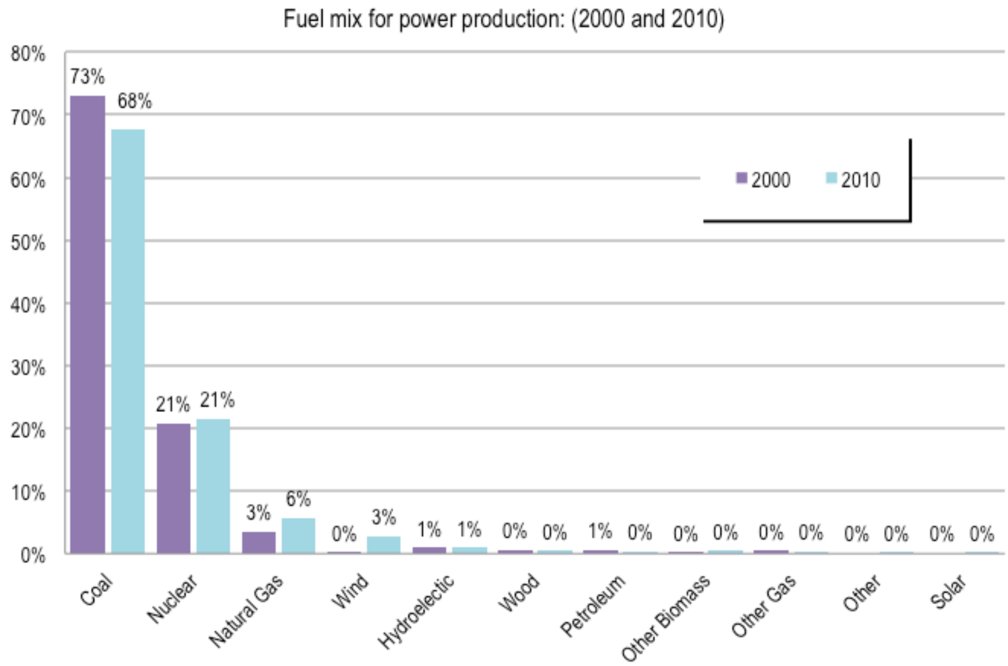

Exhibit 2. Fuel mix for power production in the Midwest region
Source: Authors' construct from EIA, "Electricity" (2010).

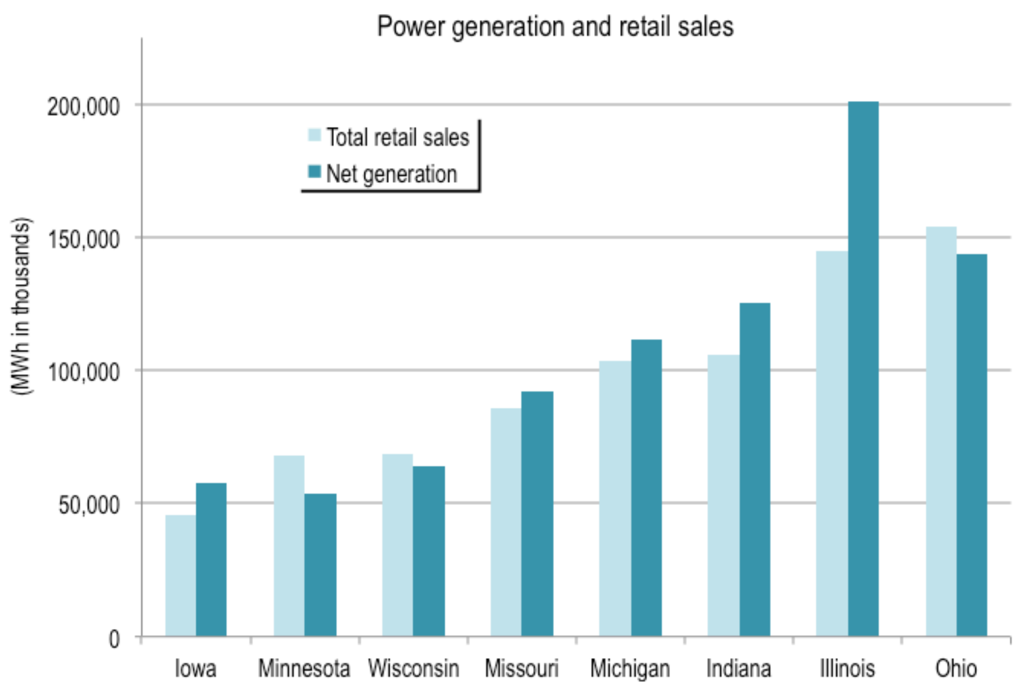

Exhibit 3. Power generation and retail sales in the Midwest region.
Source: Authors' construct from EIA, "Electricity" (2010).

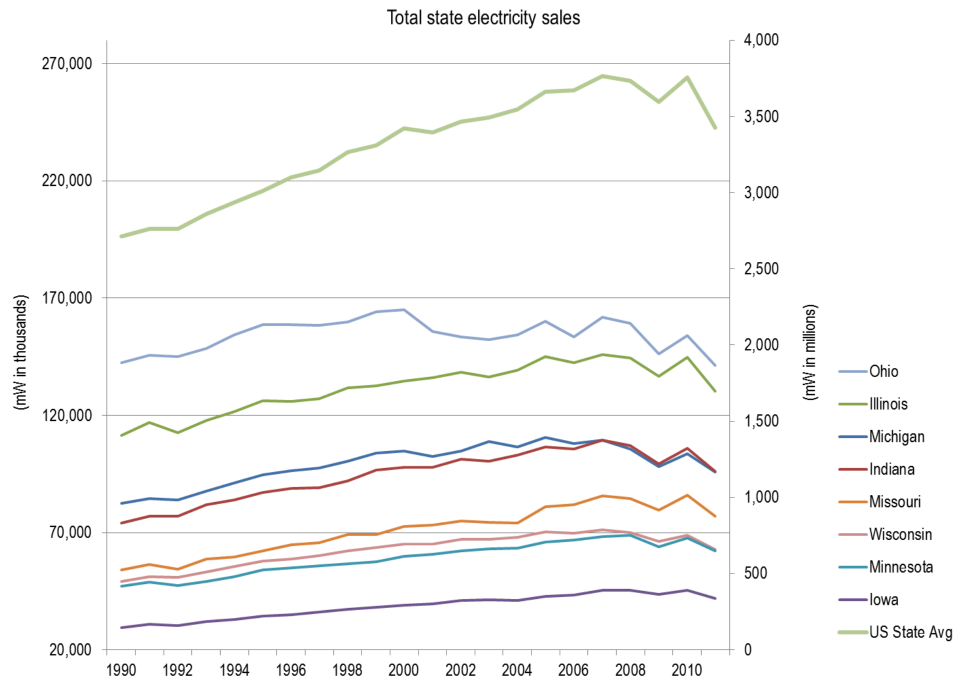

Exhibit 4. Trends in retail electricity sales in the Midwest region.
Source: Authors' construct from EIA, "Electricity" (2010).

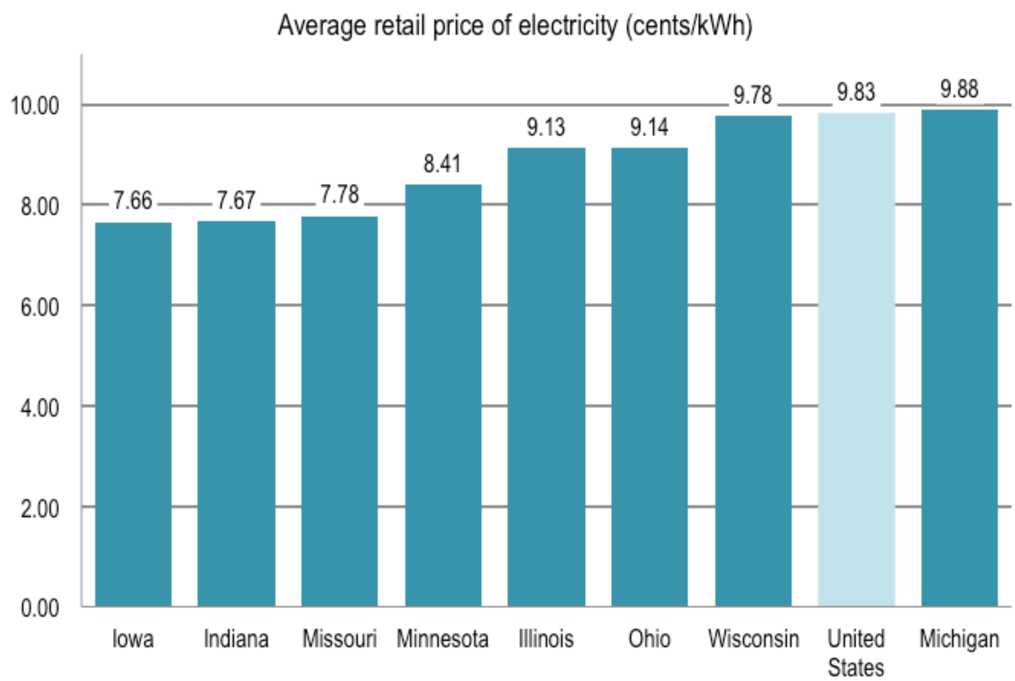

Exhibit 5. Average retail price of electricity in the Midwest region.
Source: Authors' construct from EIA, "Electricity" (2010).

2. IMPACTS ON THE ENERGY SECTOR

The impacts of climate change and climate change policy on the energy sector can be organized into demand-side and supply-side issues, as represented in the typology in Exhibit 6. The demand side considers effects on how and when energy is used by consumers. The supply side considers effects on the production of energy as well as its transmission and distribution. Demand and supply are dynamic and intersecting, so changes in one will affect the other.

Like other markets, many of the impacts described here, and the evidence that support those changes, are not unique or confined to the Midwest region. While the effects of climate change are already being felt, they may be more gradual than some of the more immediate effects of climate policy.

Exhibit 6. Typology of Climate Change Impacts on the Energy Sector

	Climate change	Climate change policy
Demand-side issues	- Changes to energy usage patterns (heating and cooling) - Health effects of heat and cold (including death) due to access and affordability - Peaking demand due to extreme weather events - Changing energy needs of other sectors, including water supply	- Demand-management mandates (standards, programs) - Load-management practices (shifting load to off-peak periods) - Energy needs of electric vehicles - Higher utility prices and price elasticity effects on demand
Supply-side issues	- Renewable energy availability (wind, solar, hydro, etc.) - Water availability and shift to power plant thermal cooling alternatives - Potential supply disruptions (reliability) - Stress on physical infrastructure from variable and extreme weather - Impact of variable demand on utility revenues and risks	- Changes to fuel portfolio of utilities - Fuel switching from coal to natural gas - Investment in alternative energy supplies, transmission facilities, energy storage, grid modernization, and back-up capacity - Environmental impacts of renewable energy development (land, aesthetics) - Effect of variable resources on reliability - Complex energy supply markets - Higher energy and water utility costs

Source: Authors' construct.

Climate Change and Energy Demand

The influence of climate change on energy usage is relatively well understood, at least in terms of consumer response to changes in weather (Cline, 1992; Smith and Tirpak, 1989). Energy is used for heating and cooling to maintain safety, comfort, and lifestyle. Individuals with the means to adapt to more extreme weather are likely to utilize technologies to these ends; individuals without the means may suffer adverse health effects. Warmer weather will induce more cooling (generally from electricity) while cooler weather will induce more heating (generally from natural gas, fuel oil, or propane) (see Gotham, et al., 2012). Increased cooling needs would increase summer-peaking electricity loads based not only on temperature but also on humidity levels. If climate change increases the duration and frequency of heat waves, as has been suggested, then electrical demands are likely to rise during summer periods (Hayhoe, et al., 2010).

In terms of energy demand, climate change may correlate with both overall trends in total usage and usage variability, as seen in patterns of average and peak demand. Changes in consumer demand are, in fact, well known by utilities, which routinely must "adapt" operations and management to weather variation and use "heating-degree days" and "cooling-degree days" for modeling and forecasting purposes. Climate change is expected to accentuate existing weather-related seasonal demand variability. The most vexing implication is that increased energy demand, particularly peak demand, would result in increased emissions if fossil fuels remain the primary fuel source for supply.

Analysts have applied different methodologies to model consumer response to changes in climate (see Mansur et al., 2008, Sailor and Munoz 1997; Rosenberg and Crosson, 1991) and considerable regional variation is recognized (Sailor 2001). Several of these studies have focused on California or the United States in general (see Baxter and Calandri, 1992; Franco and Sanstad, 2008; Aroonruengsawat and Auffhammer, 2009), although a few speak specifically to the Midwest region. As noted, models of consumer electricity demand in the context of climate change should consider not just temperature but humidity. A combined heat index that considers temperature and humidity is the best indicator for human (residential) demand for electricity (Gotham, et al., 2012).

Regional latitude is likely relevant to assessing climate change's effect on energy usage. An early study (Rosenberg and Crosson, 1991) focused on Missouri, Iowa, Nebraska, and Kansas and suggested that climate change would lead to a small increase in consumer demand for energy. Another study, however, suggested that Midwestern states may actually experience a drop in energy demand (Hadley, et al. (n.d.). The West North Central zone (including Minnesota, Iowa, and Missouri) and the East North Central zone (including Wisconsin, Illinois, Michigan, Indiana, and Ohio) could experience more cooling demand in the summer but less heating demand in the winter. At the aggregate level, energy usage was predicted to decline up until 2014 but rise thereafter. Rosenthal and Gruenspecht (1995) also anticipated a drop in energy demand, estimating that a 1 degree Celsius increase in temperature could also translate to substantial energy savings.

Forecasting energy demand has become particularly challenging given a host of exogenous influences, including economic and technological factors that could alter consumer behavior beyond climate change alone. Hekkenberg, et al. (2009) asserted that future energy demand may be underestimated by existing models because it is influenced not just by weather but also by socioeconomic trends. Fluctuations in annual income, unemployment rates, and other demographic influences may not be appropriately accounted for in existing models. Going forward, prices will also affect demand, both intrinsically and by design. While demand for utility services is *relatively* price inelastic, it is not perfectly so; in other words, price response can be expected and modeled.

Many new technologies associated with grid modernization are aimed directly at peak-demand management (that is, load shifting) in order to mitigate these effects. Some “smart grid” technologies essentially add two-way, real-time communications capabilities. With “smart meters,” customers can receive detailed information about home energy usage and costs (Giordano, 2012). Utilities can also adopt dynamic pricing for load-management purposes, although long-term efficacy must be studied. Perhaps more importantly, smart technologies can enable automation that does not rely on significant alterations either to consumer behavior or lifestyle. Although benefits to utilities are well known, much is yet to be learned about the benefits of smart technologies to utility customers and society relative to costs. Consumer acceptance remains a considerable challenge.

In addition, the effects of climate change on other sectors may change their patterns of demand, which, in turn, will affect the energy sector. For example, the water sector is highly energy intensive and changes in water demand could have positive or negative effects on the energy sector.

Climate Change and Energy Supply

Because electricity is an “on-demand” service and supply and demand must be balanced on a real-time basis, changes to demand have a direct and immediate bearing on supply. As noted earlier, climate change potentially affects consumer demand for electricity, which, in turn, will have direct impacts on energy supply over time. In effect, climate change policy is already exerting a significant influence on energy supply portfolios and the delivery infrastructure, particularly for electricity. If energy demand grows, so will production capacity needs. In the Midwest region, increased demand associated with climate change could potentially exceed 10 GW, which would require more than $6 billion in infrastructure investments (Gotham, et al., 2012).

Extreme weather associated with climate change, such as stronger, more frequent hurricanes, tornadoes, floods, and droughts, would place further burdens on the supply of electricity. Major weather events are directly related to power disruptions and outages, with damage to utility and customer equipment alike, in addition to economic opportunity costs. Loss of power is a life-threatening event and more people die of extreme heat than any other weather event (DOC, NOAA). Recovery can be costly, labor-intensive, and time-consuming and may raise significant liabilities. As such, the loss of power, or power reliability, has dire economic consequences. The cost of recovery is generally passed along to all utility customers, and the increased cost of planning for, mitigating the effects of, and recovering from catastrophe can exacerbate affordability concerns.

Climate-induced weather variation can stress infrastructure and add to the cost of initial investment as well as system operation and maintenance (Gotham, et al., 2012). Low temperatures can increase icing on overhead power lines and nearby trees. High temperatures cause metal to expand, increasing power-line sag; lack of wind worsens the problem as it prevents natural cooling of the distribution infrastructure. Excessive sag (beyond design specifications) can bring lines into contact with vegetation or even cause an arc to form within the line. Additional investment by utilities may be needed in power line monitoring (including robotic sensors), preemptive vegetation management, and even underground relocation of power lines.

Climate change also influences the performance of generation equipment (Gotham, et al., 2012; Al-Ohaly, 2003). Higher temperatures result in decreased efficiency in combustion turbines that are primarily used to generate electricity in the Midwest regions. Normally, the combustion of fossil fuels produces steam, which, in turn, moves the turbines used to generate electricity. Higher ambient temperatures lower the density of the air flowing within the system. Thus, it takes both more fuel to generate energy and more generating capacity to meet demand. In the Midwest, approximately 95% of the electrical generating infrastructure is susceptible to decreased efficiency due to ambient temperature change. As long as generators rely on steam to produce electricity, these vulnerabilities will persist (Gotham, et al.,2012).

The water-energy nexus is also important in terms of energy supply. The water industry depends on energy and the energy industry depends on water. Home to the Great Lakes, the Midwest enjoys relatively plentiful water resources. The region is also home to numerous power plants at significant scale (Exhibit 6). Thermoelectric power generation accounts for about half of total water withdrawals in the U.S., more than any other discrete function (USGS, 2009). In 2007, droughts in the Southeast jeopardized power plant operations due to their reliance on water for both steam and cooling (Manuel, 2008). Although the Midwest is not highly dependent on hydropower (Exhibit 6), fluctuations in flows will directly affect supply availability from that source (Rosenberg and Crosson, 1991). The use of pumped storage for energy adds to aggregate demand on water resources. For conventional resources, additional water storage or non-water cooling technologies may be needed. Climate change may also affect the availability and intermittency of renewable energy, including wind and photovoltaic sources. A significant consequence is the need for backup capacity to ensure reliability and resilience (see Prescott and Van Kotten, 2009).

In sum, climate change has the potential to affect power production, as well as distribution, with implications for reliability and cost. However, these effects are relatively well known to the sector, and both mitigative and adaptive strategies are being planned and deployed, in some cases in accordance with policy mandates (see Neumann, 2009).

Exhibit 6. Generation of Hydropower in the Midwest

State	Conventional Hydro MWh	Total MWh	Total Renewables MWh	Hydro as a % of total	Hydro as a % of renewable	Powered & Non-powered Dams
Illinois	136,380	193,864,357	3,666,132	0.10%	3.70%	1,504
Indiana	503,470	116,670,280	2,209,306	0.40%	22.80%	1,142
Iowa	971,165	51,860,063	8,559,766	1.90%	11.30%	3,374
Michigan	1,371,926	101,202,605	3,995,111	1.40%	34.30%	927
Minnesota	809,088	52,491,849	7,545,745	1.50%	10.70%	1,021
Missouri	1,816,693	88,354,272	2,391,498	2.10%	76%	5,099
Ohio	527,746	136,090,225	1,161,156	0.40%	45.50%	1,577
Wisconsin	1,393,988	59,959,060	3,734,283	2.30%	37.30%	1,163

Source: National Hydopower Association.
http://hydro.org/why-hydro/available/hydro-in-the-states/midwest/

Climate Change Policy

Most climate policy action in the United States has been implemented at the state or local level, in the absence of comprehensive federal policy (see Cohen and Miller, 2012). The federal government has focused much attention on subsidizing the development of clean energy sources, along with research and education in such areas as energy efficiency and "smart grid" applications. Federal regulators have promoted investment in and modernization of the high-voltage transmission grid, in part to accommodate power generation from renewable resources.

Not surprisingly, a considerable amount of state and regional climate change policy targets the energy sector with the goal of reducing emissions, particularly carbon. The considerable activity in the realm of climate change policy is already shaping demand and supply in the energy sector. States in the Midwest have joined states across the nation in adopting both climate action and energy sector policies toward this end as well as in anticipation of regional or national policies (Exhibit 7).

Exhibit 7. Climate and Energy Policy Activities in the Midwest Region

	IL	IN	IA	MI	MN	MO	OH	WI
Climate action								
Greenhouse gas	Yes			Yes	Yes			
Emissions cap for	Yes							
Climate action plans	Yes		Yes	Yes	Yes	Yes		Yes
Climate comms. & adv.	Yes		Yes	Yes	Yes			Yes
Regional initiatives	Yes(1)	Yes(2)	Yes(1)	Yes(1)	Yes(1)	Yes(3)	Yes(1)	Yes(1)
GHG climate registry	Yes		Yes(4)	Yes	Yes	Yes	Yes	Yes(4)
State adaptation plans			Yes	Yes	Yes(5)			Yes
Energy sector								
Public benefit funds	Yes(RE)			Yes(RE)	Yes(R)			Yes(RE)
Renewable or alt.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Net metering programs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Green pricing programs	Yes				Yes			
Decoupling policies	Yes(G)	Yes(G)						Yes(EG)
Renewable energy	Yes		Yes		Yes			Yes
Energy efficiency	Yes(EG)	Yes(E)	Yes(EG)	Yes(EG)	Yes(EG)		Yes(E)	Yes(EG)
Financial Incentives for	Yes	Yes			Yes			

(1) Midwest GHG Reduction Accord & Platform; (2) MGGRA Observer & Midwest Platform; (3) Midwest Platform; (4) Mandatory reporting also required; (5) In progress; (E) Electricity, (G) Gas, (EG) Electricity and Gas; (RE) Renewable energy and efficiency; (R) Renewable energy.

Source: Center for Climate and Energy Solutions
http://www.c2es.org/what_s_being_done/in_the_states/state_action_maps.cfm

Demand-side policies for the sector are focused on reducing energy load through end-use efficiency (load reduction) as well as shifting load to off-peak periods for more efficient utilization of power plant capacity (thus avoiding the need for extra capacity to meet peak demand). Price plays a critical role in cost recovery as well as an incentive-based tool of demand management. Real-time prices and demand-response programs take advantage of price elasticity to encourage load shifting by consumers. Demand-side programs are designed to accelerate deployment of efficiency practices in areas such as heating, cooling, and lighting.

Climate change policy looks to the supply side with the intention of shifting away from reliance on greenhouse gas-emitting fossil fuels and toward clean and renewable energy alternatives. Leading policies include state-level renewable portfolio standards (RPS), with various specifications and timetables, which in many respects are an alternative to carbon taxes or markets (also known as cap and trade). These changes will affect resource and labor markets as well as land-management practices. For example, wind and biomass siting and development have significant implications for the agricultural sector. The effects of renewable energy development are likely to vary across and within states, depending on resource availability, land and water characteristics, economic profile, and state and local policies.

Much policy attention has also focused on utility incentives and compensation for developing cleaner generation options and promoting energy efficiency. Carbon capture and storage solutions or "clean coal" have received some attention although significant technical challenges remain (see Graus, et al., 2011). Net metering laws allow consumers to sell excess power produced by renewable technologies back to the power company. Grid modernization and "smart" technologies (including smart meters) are regarded as enabling supply-side resource integration as well as demand management. Any large-scale use of electricity or natural gas for transportation will have a significant impact on energy markets.

Future Considerations & Issues

A perennial issue in the energy sector concerns the true cost of electricity. Direct and indirect subsidies, and environmental externalities, distort prices. When true costs are not accurately reflected in price, production and consumption are inefficient. In the past, traditional fossil fuels enjoyed preferential policies' renewable resources are similarly advantaged today. To many economists, putting a price on carbon via a tradable market or tax would promote more efficient choices among competing technologies for lowering greenhouse gas emissions (see Parry and Williams, 2010; Burtraw, 2011).

Without a level playing field or preferential policy treatment, development of alternative energy might be cost prohibitive. Many resource alternatives raise significant technical challenges in terms of supply chains, intermittent availability, and the lack of cost-effective means of energy storage. Long-distance transmission needs and costs are also significant, particularly for wind energy (Yang, 2009). Some have argued, however, for development of lower-velocity local resources (Hoppock and Patino-Echeverri, 2010). The potential for high costs and lower reliability looms large, with significant economic and social implications, particularly affordability of an essential service (see Berger, 2009). The accurate comparison of resource alternatives requires a total life-cycle cost analysis. The regressive nature of utility prices argues further for awareness of the distributional consequences on households and attention to rate design (Beecher, 2012a).

Utility infrastructure is especially capital intensive and long-lasting. Changing the resource mix and operational profile is a formidable proposition, particularly given sunk costs and underlying concerns about meeting service obligations. Utilities also have a tradition of long-term capacity planning and their planning processes are already incorporating adaptive strategies, in part due to policy mandates. Utility investors and managers are not necessarily averse to responsible climate change policy, but it is widely understood that they prefer a context of more regulatory certainty to less, particularly with regard to cost recovery. Many have argued for policy and regulatory reforms, including special financial incentives for utilities. But the central role of economic regulation is the assurance of prudent compliance with policy mandates and the fair allocation of risks and costs among utilities and their customers.

As for all sectors, while some degree of skepticism remains about the causes and consequences of climate change for the energy sector, a fair amount of consensus exists in the community about the relevance of climate change. Despite a large amount of attention and research, the sector suffers from limited evidence and contradictory speculation with regard to potential impacts and their extent. Logically, if not empirically, larger changes in climate are likely to present larger challenges and consequences.

The Midwest region will experience climate change and climate change policy in ways similar to the rest of the country. The region may be advantaged by its northern latitude and relatively abundant water resources. The challenge may still be considerable but, in theory, it should be more manageable than in regions facing more stressful conditions. Regardless of climate *change,* climate change *policy,* along with related energy policy mandates, will likely have an indelible impact on the provision and cost of essential energy services. Energy utilities are already anticipating and adapting, in part to manage regulatory uncertainties. The generational challenge of climate change policy will be to strike a workable balance among the goals of clean, reliable, and affordable energy.

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HEALTH

Jonathan Patz

Introduction

Many human diseases are sensitive to climate fluctuations, including those that occur in the Midwest US. More direct pathways through which climate change can adversely affect health include: heat-related morbidity and mortality; flooding and storms with associated trauma and mental health concerns; air pollution, especially from ground-level ozone, particular matter (PM) and potentially from aeroallergens (e.g., pollen and molds); and infectious diseases, particularly those that are water- or vector-borne. Land use changes happening alongside climate change can make human health problems worse. For instance, the 'urban heat island effect' could make future heat waves more severe for city-dwellers.

Downscaled global climate models for our region indicating that the most likely types of climate change will be: (a) reductions in extreme cold; (b) increases in extreme heat; (c) increases in extremely heavy precipitation events; (d) greater precipitation during winter and even more so during spring; and (e) warming in every month/season (Vavrus and Van Dorn 2009).

We can only assess future health risks to the extent that climate/health mechanisms are understood and quantitative health models are available. Some health issues in the region may benefit from climate change, such as a reduction in cold-related deaths. But, on balance, a review of the literature suggests that the adverse health ramifications outweigh potential health benefits. Of course, in addition to future climate projections, varying scenarios of future demographic and economic trends adds uncertainty for assessing human population vulnerability.

Current Climate Sensitivities and Projected Risks for the Great Lakes Region

Heat Waves

Heat waves are a well known cause of mortality. For example, the 1995 Upper Midwest heat wave resulted in 700 deaths in Chicago (Semenza et al. 1996). During the same heat wave, 91 deaths and 95 paramedic emergency medical service (EMS) runs in Milwaukee were attributed to heat.

Currently for the US, mortality increases nearly 4% during heat waves compared with non-heat wave days (Anderson and Bell, 2010). Risk of death increased 2.5% for every 1°F increase in heat wave intensity and 0.4% for every 1-day increase in heat wave duration. Mortality increased 5.0% during the first heat wave of the summer versus 2.7% during later heat waves, compared with non-heat wave days. Heat wave mortality impacts are more pronounced in the Northeast and Midwest regions compared with the South (Anderson and Bell, 2010).

According to Peng et al (2010), under three different climate change scenarios for the period 2081–2100 (in the absence of adaptation) the city of Chicago could experience between 166 and 2,217 excess deaths per year attributable to heat waves, based on estimates from seven global climate models. The authors noted considerable variability in the projections of annual heat wave mortality; the largest source of variation was the choice of climate model (Peng et al 2010). Regarding morbidity, analysis of heat wave admissions to hospitals in the city of Milwaukee found an increase in admissions for endocrine, genitourinary, and respiratory disorders, as well as self inflicted injuries such as from suicide attempts (Figure 1). (Li et al, 2011).

Air Pollution Risks

Air Quality and Respiratory Disease

Estimates of the impact of global climate change processes on the formation of ozone air pollution have been conducted for Chicago, IL. Projected meteorological changes alone are expected to increase ground-level ozone by an average of 6.2 ppb (under low-growth scenarios) to 17.0 ppb (under high growth scenarios) in the summer months by the end of the current century, translating into an associated three-fold (low-growth) to eight-fold (high growth) increase in the number of exceedances of the current 84 ppb National Ambient Air Quality Standards (NAAQS) for ozone (figure 2) (Holloway et al. 2008).

Aeroallergens

Higher levels of carbon dioxide promote growth and reproduction by many plants, including those that produce allergens. For example, ragweed plants experimentally exposed to high levels of carbon dioxide can increase their pollen production several-fold, perhaps part of the reason for rising ragweed pollen levels in recent decades (Ziska and Caulfield, 2000; Wayne et al., 2002). In a recent nationwide study, significant increase in the length of the ragweed pollen season was found to have increased be as much as 13–27 days at latitudes above ~44°N since 1995 (Ziska et al. 2010).

Waterborne Disease

Heavy precipitation events have been implicated in outbreaks from waterborne pathogens in the United States and follow a distinct seasonality and spatial clustering pattern in key watersheds (Curriero, Patz et al. 2001). Certain watersheds, by virtue of the land use patterns and the presence of human and animal fecal contaminants, are at higher risk of surface water contamination after heavy rains, and this has serious implications for drinking water purity. Intense rainfall can also contaminate recreational waters and increase the risk of human illness (Schuster, Ellis, Robertson et al. 2005) through higher bacterial counts. This association is strongest on the beaches closest to rivers (Dwight, Semenza, Baker and Olson, 2002).

The northeast and Great lakes regions contain many older cities that have combined sewer systems –which handle both sewage and stormwater together in large underground pipes). When these systems become inundated with rainwater following heavy precipitation they can overflow into receiving waters, presenting a health risk from contaminated surface water. The EPA estimates that there are more than 3 trillion liters of un-treated combined sewage released annually (US EPA 2004). Most water resource managers and civil engineers in urban areas acknowledge unrecognized sewage contamination as a serious problem, but have no idea of the magnitude or the dynamics of how contamination occurs.

The frequency and intensity of heavy precipitation already have been increasing and account for a rising percentage of total precipitation in the Midwest region (Ebi 2008). These events have increased in frequency by as much as 100% (Kunkel 2003). Heavy rainfall has been associated with water-borne disease outbreaks – most notably the 1993 *Cryptosporidium* outbreak in Milwaukee WI, exposing an estimated 405,000 people and causing 54 fatalities (Curriero, Patz et al. 2001).

For the Great Lakes region of the US, contamination events typically occur when daily rainfall levels exceed a threshold approximating 2 to 2.5 inches (Hayhoe et al, 2007; McLellan et al, 2007). Given that heavy rainfalls are expressions of climate, there is heightened concern as to how this type of event may change in a warmer future climate.

Precipitation intensity (total precipitation divided by the number of wet days) is projected to increase almost everywhere, particularly in middle and high latitudes where mean precipitation is also expected to increase (Tebaldi, 2006). Most of the Great Lakes region is projected to experience a rise in mean and intense precipitation events (IPCC, 2007; Diffenbaugh et al, 2005).

Analysis of downscaled Global Climate Models (GCM) predict with high certainty that climate change will lead to increases in heavy precipitation with greater winter and spring precipitation for the state of Wisconsin (Vavrus and Van Dorn 2009). Overall, the models project that these extremely heavy precipitation events will become 10 to 40% stronger in southern Wisconsin, resulting in greater potential for flooding and water-borne diseases that often accompany high discharge into Lake Michigan (Figure 3) (Patz et al, 2008).

The combination of future thermal and hydrological changes may affect the usability of recreational beaches. Chicago beach closures are dependent on the magnitude of recent (<24-hour) precipitation, lake temperature, and lake stage (Olyphant and Whitman, 2004). Projected increases in heavy rainfall, warmer lake waters, and lowered lake levels (Kunkel et al, 2007) would all be expected to enhance beach contamination in the future. Although more intense rainfalls would seem to contradict the projection of lower lake levels, the latter expectation stems from a large anticipated increase in evaporation at the lake surface (which can offset the precipitation gain) and a higher proportion of future precipitation falling as heavy events, even if the total precipitation amount does not rise.

Vectorborne Infectious Diseases

Diseases carried by insects are sensitive to climate fluctuations such as Saint Louis encephalitis (SLE) and West Nile virus. West Nile virus (WNV) emerged for the first time in the North America in July 1999. While international travel is suspected as the cause of this event, the unseasonable heatwave that year (as well as in subsequent hot summers in the Midwest and West during peak years of 2002 & 2003 subsequently) raises the question of weather's possible effect on WNV disease ecology and transmission. An outbreak of West Nile encephalomyelitis in horses in the Midwest of the US peaked with high temperatures, and significantly dropped following decreasing ambient temperatures, suggesting a temperature effect (Ward, 2004). Bird migratory pathways and WNVs recent march westward across the US and Canada are key factors as well, and must be considered in future assessment of temperature's role in disease dynamics.

Lyme Disease

Lyme disease is the most prevalent zoonotic disease in the North America for which there is new evidence of an association with temperature (Ogden et al. 2004). Two main foci of disease occur in the Mid-Atlantic region and in western Wisconsin along the Mississippi valley. In the field maximum, minimum, and mean temperatures as well as vapor pressure significantly contribute to the abundance this tick, *Ixodes scapularis,* in the US. Also, an average monthly minimum temperature threshold above –7°C is required for tick survival (Brownstein, 2003).

Current Adaptive Capacity

Heat waves

Air conditioning is one adaptation to heat waves, and increasing trends in air conditioning market saturation and may substantially offset direct risks of more frequent heat waves (Sailor and Pavlova, 2003). However, use will increase the demand for electrical power and subsequent production of pollution and greenhouse gases – potentially an unsustainable adaptation, unless demand for electricity can by generated by renewable sources (e.g, wind and solar).

Heat response plans and heat early warning systems (EWS) can save lives. For example, in the wake of the 1995 heat wave, the city of Milwaukee initiated an “extreme heat conditions plan” that almost halved heat-related morbidity and mortality (Weisskopf et al. 2002). As for EWS, currently, over two-dozen cities worldwide have a “synoptic-based” weather watch-warning system, which focuses monitoring on dangerous air masses (Sheridan and Kalkstein, 2004). However, variability in predictability between cities suggests that systems must be location specific, requiring the input of considerable amounts of health-related and meteorological data for each locale at considerable costs.

Health Co-benefits of GHG Mitigation

Energy

A recent study by Shindell et al. (2012) addressed tropospheric ozone and black carbon (BC) contribution to both degraded air quality and global warming. The authors identified 14 best interventions targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050. The resulting "co-benefit" was the avoidance of 0.7 to 4.7 million annual premature deaths from outdoor air pollution and increases annual crop yields by 30 to 135 million metric tons due to ozone reductions in 2030 and beyond. The valuation was dominated by health effects from reduced BC in the air. While this study was global in nature, the findings apply to any location with coal-fired power plants, the most substantial contributor to black carbon particulates.

Transportation

Case study: Co-Benefits of Alternative Transportation Futures from improving air quality and physical fitness

The transportation sector produces one-third of U.S. greenhouse gas emissions. Automobile exhaust contributes not only to GHGs but also contains precursors to fine particulate matter ($PM_{2.5}$) and ozone (O_3), posing public health risks. Adopting a greener transportation system with fewer automobiles, therefore, could have immediate health "co-benefits" via improved air quality. Grabow et al. (2012) modeled census tract-level mobile emissions for two comparative scenarios: current baseline versus a green scenario where automobile trips shorter than five miles round-trip would be removed for the 11 largest metropolitan areas in the Midwestern U.S. These relatively short car trips comprised approximately 20% of vehicle miles traveled for the region

Across the upper Midwest study region of approximately 31.3 million people and 37,000 total square miles, mortality would decline by nearly 575 deaths per year (95% CI: 912, 1,636) from the benefit of improved air quality. Health benefits would also accrue in rural settings as well, with 25% air quality-related health benefits to populations outside metropolitan areas.

An active transport scenario was then added, with the assumption that 50% of the short trips (<5 miles) could by achieved by bicycle during the four months of most favorable weather conditions in the region. This theoretical maximum level of biking was selected because some locations in Europe have achieved this amount of bicycle commuting, and there already exists an observed trend of increasing bicycle share across all of the 11 midwestern metropolitan areas (US Census 2008). This active transport scenario alone yielded savings of another 700 lives/year and approximately $3.8 billion/year from avoided mortality costs (95% CI: $2.7, $5.0 billion].

In summary, the estimated benefits of improved air quality and physical fitness from a green transportation scenario would be 1300 lives saved and $8 billion costs avoided per year for the upper Midwest region alone. Nationally, there is already evidence that U.S. cities with enhanced levels of active transport experience large health benefits; one study found that cities with the highest rates of commuting by bike or on foot have obesity and diabetes rates 20 and 23% lower, respectively, than cities with the lowest rates of active commuting (Pucher et al 2010).

Conclusion

The Midwest region is one that remains vulnerable to health risks from climate change and associated extremes in climate variability. While some capacity to adapt is evident for the region, aging infrastructure poses concomitant risk, especially in the case of municipal water systems. Health benefits accruing from greenhouse gas mitigation can be large, as shown by a green transportation scenario. Therefore, such health benefits (e.g. 1300 lives/year saved in our region) must be included in any assessments and policy discussions related to energy production or transportation planning.

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Figure 1 (source: Li et al., 2011)

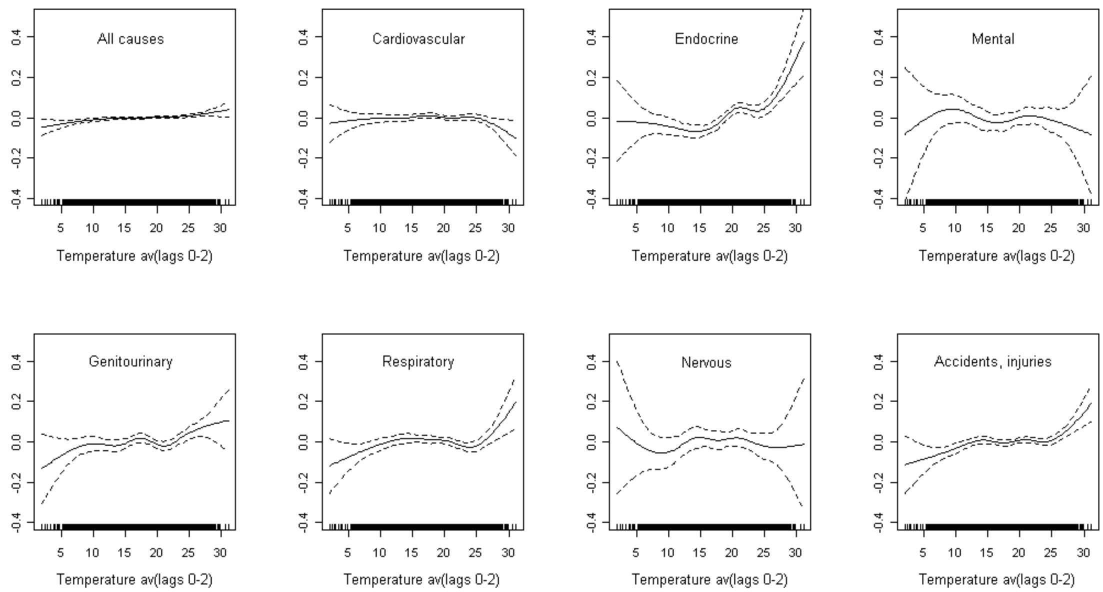

Figure 2. Projected increases in ozone in Chicago (Source: Holloway et al. 2008).

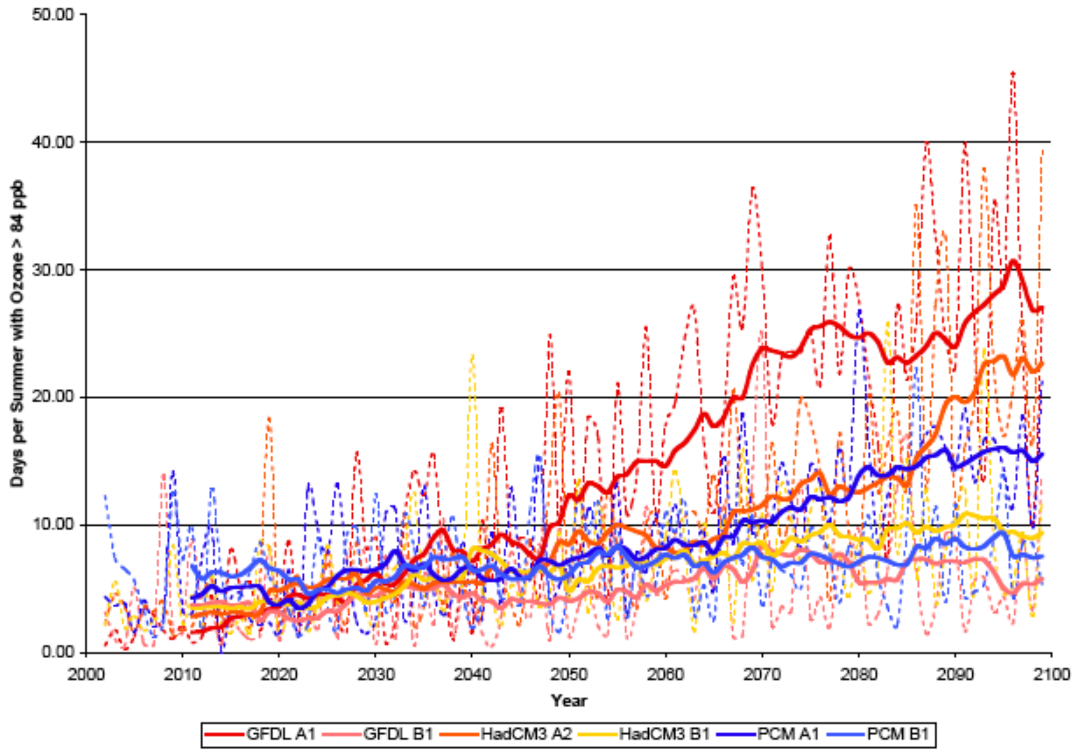

Figure 3.

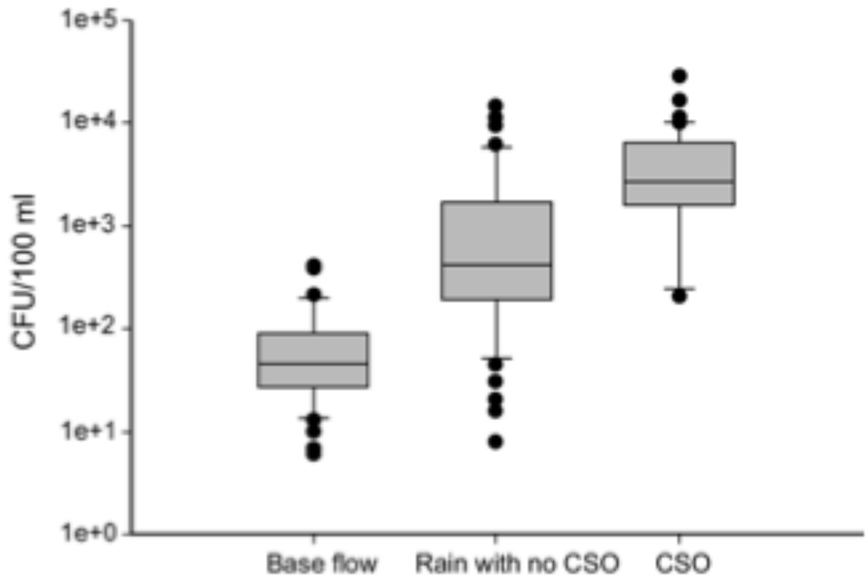

Figure 4. Levels of *E. coli* in the Milwaukee estuary, which discharges to Lake Michigan, 2001–2007, during base flow (n=46); following rain events with no CSO (n=70); and following CSO events (n=54). Boxes indicate 75% of values, with median values drawn in each. Whiskers are 95% of values and outliers are shown as closed circles. There were significant differences in *E. coli* levels following rainfall and CSOs compared to base flow ($p \leq 0.05$).
CFU, colony forming units; CSO, combined sewer overflow

Outdoor Recreation and Tourism

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Executive Summary

- Climate variability and change have both direct and indirect implications for outdoor recreation and tourism activity. Direct implications stem from changes in key climatic variables that may directly impact the feasibility of outdoor recreation and tourism activities, or levels of satisfaction with them. Indirect implications result from projected changes in the natural environment, as a result of climate variability and change, which will cause secondary impacts on visitor behavior and experience.
- Climate variability and change have implications for both the supply of outdoor recreation and tourism resources and settings, and the demand for outdoor recreation and tourism activities and experiences.
- Anticipating the reaction of outdoor recreation and tourism participants to climate variability and change is complicated. Weather and climate are but one of a series of factors that influence outdoor recreation and tourism decisions. Moreover, changing climatic and environmental conditions, resulting changes in the feasibility and safety of activities, and alterations in the level of enjoyment associated with activity participation, may cause participants to alter one or more of the frequency, duration, timing, and/or location of future activity, or to shift participation to an entirely different activity altogether.

Defining Outdoor Recreation and Tourism

The terms recreation and tourism are notoriously difficult to define and differentiate, and the semantics of these seemingly simple words have been discussed at length in a variety of text books and industry publications. For the purposes of this chapter, tourism will be taken to refer to travel some distance (typically 50 miles) away from home for some length of time between 24 hours and one year, for the purpose of business or leisure, whereas outdoor recreation will be assumed to have no spatial or temporal boundaries or restrictions. Thus, outdoor recreation may take place anywhere, from an individual's back yard to a local park to a distant location, i.e., while engaging in tourism.

The Importance of Travel and Tourism to the US Economy

The contribution of the travel and tourism industry to the US economy is significant. Travel and tourism is the nation's largest services export industry, and accounts for 2.7% of the nation's gross domestic product. In 2010, travel and tourism activity generated $1.8 trillion in economic output, with the $759 billion spent directly by domestic and international travelers in the nation stimulating an additional $1 trillion in indirect and induced economic activity. In addition, the travel and tourism industry supports approximately 14 million jobs. The 7.4 million jobs directly related to travel and tourism generated $188 billion in payroll in 2010, while another 6.7 million individuals work in positions indirectly related to travel and tourism, in industries such as construction, finance, etc. These 14 million travel and tourism jobs represent one in every nine non-farm forms of employment across the nation. In terms of tax revenue, travel and tourism directly generated $118 billion for local, state and federal governments in 2010 (US Travel Association, 2011). Figure 1 illustrates the contribution of travel and tourism to the economies of the Midwest states in terms of visitor spending, tax receipts, direct jobs created, and payroll generated.

Outdoor Recreation and Tourism (ORT) and Climate Variability and Change (CVC)

According to Hall and Higham (2005, p. 21), "[I]n terms of the future of tourism, as well as the societies within which we live, there are probably few policy and development concerns as significant as global climate change." These authors go on to note that, "Understanding and responding to climate change represents one of the more important, complex and challenging issues facing the contemporary tourism and recreation industries" (Higham & Hall, 2005, p. 307). The complexity to which Hall and Higham alludes results from a combination of factors related not only to the difficulties associated with projecting climate change and its potential impacts on the natural environment, but also to the added complication of incorporating the human reaction to such change into the analysis.

Direct and Indirect Implications of CVC for ORT

Climate variability and change have both direct and indirect implications for ORT activity. The direct implications of CVC for ORT activity relate to changes in key climatic variables that may directly impact the visitor experience. For example, changes in temperature, precipitation, wind speed, humidity, or snow depth may have a direct effect on (i) the feasibility of ORT activities, and/or (ii) levels of safety associated with participation in ORT activities, and/or (iii) the quality of the experiences of those who do participate in them. Modifications to climatic conditions, resulting changes in activity feasibility and safety, and alterations in the level of enjoyment associated with activity participation, may cause participants to alter the frequency, duration, timing, and/or location of future activity, or even to shift participation to an entirely different activity altogether.

Climate variability and change may also alter the distributions and compositions of natural resources such as the flora and fauna found at an ORT destination. Since much ORT activity focuses on the viewing, photographing, hunting and/or fishing of such species, the implications of shifting habitat zones are profound. Such shifts in the quality and quantity of wildlife and vegetation may cause indirect, or secondary, impacts on ORT activity, as participants alter their activities to account for changes in the natural environment as a result of climate variability and change.

Implications of CVC for ORT – Supply and Demand Side Factors

As suggested above, CVC will likely have implications for both the natural environment and the visitor experience of that environment. These implications can therefore be separated into consideration of implications for supply (how CVC might impact the natural environment and the associated supply of ORT resources) and demand (how CVC might impact participant demand for activities and destinations). As suggested previously, while projection of climate change and its potential impacts on the natural environment is complex, addition of humans – outdoor recreationalists and tourists – to the equation adds an additional layer of complexity. This additional complexity results from two important human dimensions: (i) the myriad of influences – besides weather and climate – on ORT decisions, including the availability of free time and disposable income; family commitments; economic situations in origins and destinations; prices; exchange rates; political, military and safety considerations in destination regions; media coverage; and, shifting fashions; and (ii) the myriad of response options available to ORT participants, including in which activities (i.e., in what) to participate or to which destinations (i.e., where) to travel, when, for how long, how often, etc. Given the huge number of recreation activities and tourism destinations from which modern consumers choose, the opportunity for substitution, in one or more dimensions, is tremendous, and, as a result, extraordinarily difficult to model effectively.

While the specific adaptive behavior of the ORT participant may be difficult to envisage, it is clear that in general the adaptive capacity of such participants is quite high. As noted above, outdoor recreationalists and tourists control the activities in which they choose to participate and the destinations to which they choose to travel, as well as various aspects of the timing of these choices. The modern, technology-based era has also facilitated the phenomenon of last-minute booking, which further increases traveler's flexibility and responsive to unanticipated change. As discussed in the European context by Nicholls and Amelung (2008), however, the tourism industry itself, i.e., ORT providers, face lower, or at least slower, levels of adaptive capacity, much of which may be attributed to a combination of spatial fixity and sunk costs. Accommodations, food and beverage outlets, and built attractions and facilities such as theme parks and marinas are all fixed entities with considerable capital investments that are not easily liquidated or shifted. Similarly, natural attractions such as national and state parks are static entities with defined boundaries. Faced with minimal opportunity to physically relocate in response to changes in the climate, tourism providers may be forced to consider a variety of alternative adaptation techniques in order to sustain their businesses.

Implications of Climate Variability and Change (CVC) for Outdoor Recreation and Tourism (ORT) in the Midwest

The projections with regards to climate variability and change for the Midwest area as laid out in other chapters of this report suggest a wide variety of implications for participation in outdoor recreation and tourism activities, as well as for the sustainability of the industry that supports these activities. Table 1 outlines the most significant climate change projections for the Midwest region and the potential implications of these projected changes for ORT. As illustrated, these implications reflect potential changes in both the supply of, and the demand for, ORT settings and associated activities.

Consideration of increasing temperatures raises the interesting question of the existence of thresholds for ORT activity. From a supply perspective, some thresholds are fixed, e.g., current snowmaking technologies within the US generally require conditions below 28ºF wetbulb for operation. In the case of consumers, however, scientific knowledge is more limited. For example, though it has been established that the typical tourist prefers a temperature of 21ºC at their holiday destination (Lise & Tol, 2002), these authors rightly cautioned that this average camouflages variations in preferences by country or region of origin (i.e., nationality), as well as by travelers' ages, incomes, and preferred activities. Thus, it is likely that the acceptable maximum temperature or heat index level above which ORT activity becomes unbearable will also vary with activity and location. Establishment of such thresholds, and identification and understanding of the implications of behavioral responses to them, represents a pressing need within CVC/ORT research. The existence of such thresholds has implications for providers too, for example, the need to consider indoor alternatives for visitors on extremely hot days and increasing demand for air conditioning capabilities.

In the bullet points that follow a sampling of the indirect implications of CVC for ORT, via modifications to the natural environment which serves as the backdrop for ORT activity, is provided. It should be noted that the current volume of scientific work specifically addressing the implications of CVC for ORT in the Midwest region is extremely limited, and thus this summary represents the range and depth of knowledge currently known:

- Reductions in Great Lakes levels (projected towards end of century under higher emissions scenarios by some authors, e.g., Hayhoe, VanDorn, Croley II, Schlegal & Wuebbles, 2010) – lower lake levels could have a multitude of implications for ORT. These include: reduced access to the water, e.g., due to the increased inaccessibility of existing public and private boat ramps, docks and marina facilities; the increased need for and cost of dredging and channel maintenance: an increase in the presence of hazardous conditions such as newly exposed navigational hazards and sand bars; increased competition between ORT and other lake users, e.g., navigation, power generation, residential, industrial and agricultural use; a decline in the aesthetic appeal of lake-side locations; and, reductions in lake-side property values and a resulting decline in the local tax base.
- Warming waters and declining water levels in lakes and streams – such alterations have implications for the habitat of cold-water fish species such as brook trout and walleye, and for warmer-water species such as bass, with the extent of habitat in the Midwest projected to decrease for the former and increase for the latter. These shifts have concomitant implications for the distribution of these species and the ability to fish them, whether for commercial or recreation purposes.

- Alterations to shoreline wetlands – such alterations have implications for the habitat of breeding and migrating waterfowl, with concomitant implications for the distribution of these species and the ability to view, photograph and/or hunt them.
- The effect of warming air and water temperatures on the presence of algae and invasive species – warmer conditions may exacerbate existing and generate new problems with algal blooms and with invasive species such as phragmites and zebra mussels. Such species can stress native species and reduce the aesthetic quality of ORT settings, thereby decreasing their attractiveness and negatively impacting the visitor experience.
- The effect of warming temperatures on the distribution of plants and trees – fall leaf viewing represents an important component of the tourism economy in many parts of the Midwest. The redistribution of suitable habitat for critical species such as maple and aspen could impact the viability of fall leaf tours by both auto-based individuals and coach-based groups.
- The effect of warming temperatures in urban areas – besides the discomfort associated with excess heat and the potential need for increased air-conditioning capabilities, warming in urban areas such as Chicago and Detroit could increase levels of ground-level ozone and hence exacerbate respiratory problems such as asthma among the traveling public. Such conditions have implications not only for leisure visitation but also for business travel, since major urban areas typically rely heavily on corporate activities such as meetings, exhibitions and conventions for a large proportion of their travel business.
- The increased risk of fire due to warmer and/or drier conditions – fire presents both immediate and secondary implications for ORT activity, from both a safety perspective and the impacts of fire damage on the aesthetic appeal of a location.
- The increased presence of insects and pests due to warmer and/or wetter conditions – insects and pests present several implications for ORT activity, including from a health and safety perspective (i.e., the potential for the increased spread of disease) and the perspective of human comfort/the visitor experience, e.g., camping and other outdoor activities are less desirable in the presence of large volumes of mosquitoes or black flies.

Application of the Tourism Climatic Index (TCI)

The Tourism Climatic Index was first developed by Mieczkowski (1985). The TCI allows quantitative evaluation of a location's climate for the purpose of general outdoor tourism activity, such as sightseeing, visiting a state or national park, etc. The TCI is based on the notion of "human comfort" and consists of five sub-indices, each represented by one or two climate variables. The five sub-indices and their constituent variables are as follows: (i) daytime comfort index (maximum daily temperature and minimum daily relative humidity), (ii) daily comfort index (mean daily temperature and mean daily relative humidity), (iii) precipitation, (iv) sunshine, and (v) wind speed. The index is weighted and computed as follows: $TCI = 4CID + CIA + 2R + 2S + W$, where CID = daytime comfort index, CIA = daily comfort index, R = precipitation, S = sunshine, and W = wind speed. With an optimal rating for each variable of 5.0, the maximum value of the index is 100. Based on a location's index value, its suitability for general outdoor tourism activity is then rated on a scale from –30 to 100. Mieczkowski then rated the resulting range of comfort levels as shown in Table 2. The TCI has been combined with projected scenarios of future climate conditions in order to assess potential changes in the climatic attractiveness of locations for general ORT activity in North America (Scott, McBoyle & Schwartzentruber, 2004;

Nicholls, Amelung & Viner, 2005), Europe (Amelung & Viner, 2006; Nicholls & Amelung, 2008) and at the global level (Amelung, Nicholls & Viner, 2007). The TCI allows consideration of the direct implications of CVC for ORT supply conditions, though it should be noted that the TCI is not applicable to the winter sports/tourism sectors.

Figures 2-7 illustrate shifting distributions of climatic attractiveness for the Midwest region and for the wider US for the coming century. The months of January and July are represented, based on the A2A scenario with the HadCM3 GCM, thus the shifts illustrated are towards the more extreme end of the projected change spectrum (a "high climate future"). As might have been anticipated, winter conditions are currently and will in the next century likely remain unsuitable for general ORT activity in the Midwest. Of greater interest and potential concern are the projected changes in conditions in the summer period. While current conditions range from acceptable in the southern portions of the Midwest region, through good to very good for most of the region, to ideal to excellent within certain pockets, by the 2080s the distribution of these conditions is projected to shift northwards, with the Midwest experiencing unfavorable conditions across most of its southern portion and acceptable conditions in the north. These projected changes in climatic attractiveness reflect the increasing heat and humidity projected for the area, and the resulting decline in the desirability of being outdoors and engaging in ORT activity.

Implications for Winter Sports

The Midwest region as defined in this report accounts for nearly one-fifth of ski areas throughout the United States (Table 3) and the winter sports sector is extremely vulnerable to the impacts of climate variability and change. Nevertheless, consideration of the implications of CVC for this sector and region in the literature is minimal. Most of the work on winter sports has been conducted in either a European or a Canadian context, and the majority of that work focuses on supply (i.e., the provision of adequate levels of snow) rather than demand (i.e., winter sports consumers' behaviors) issues.

That being said, one of the earliest pieces of work on the implications of CVC for winter sports was in fact conducted in Michigan (Lipski & McBoyle, 1991). Using two scenarios of projected increases in temperature and precipitation of 6ºF and 9%, and 9.7ºF and 11%, respectively, they projected changes in the number of reliable winter days, i.e., days with sufficient snow cover for downhill skiing, at three ski areas throughout the state. For those three areas studied, with then current (i.e., 1990) numbers of reliable ski days in the order of 100, 79, and 59, respectively, Lipski and McBoyle projected declines to 62, 41 and 10 reliable days under their first, less extreme scenario, and the complete elimination of the industry, i.e., zero reliable days at any one of their study sites, under the second and more extreme scenario. This study did not incorporate the impacts of snowmaking capabilities on the occurrence of reliable days, whereas more recent analyses in other regions have been able to factor in this consideration, thereby providing more realistic indications of impact on skiable days (e.g., Scott, McBoyle & Mills, 2003; Dawson, Scott & McBoyle, 2009).

Understanding of skiers' reactions to current as well as projected future conditions are complicated by the widely–held belief within the industry that ski activity is impacted as much as, if not more than, by weather conditions at the skier's place of origin and by the weather forecast for the coming weekend than it is by actual conditions on the slopes. Though this hypothesis has yet to be empirically supported, it does suggest the additional challenges that ski areas may face in recruiting customers under warmer conditions with less natural snow, even if snowmaking technologies are sufficient to keep the slopes themselves open for business.

Adaptation

It is critical to note that the climate changes projected suggest that there will very likely be both winners and losers from the perspective of the ORT industry. Risks and opportunities arise both directly, as a result of changing climatic conditions within a destination region, as well as indirectly via any one enterprise's ability to adapt to those changing conditions in situ. For example, while winter sports may be devastated by rising winter temperatures (which would not only reduce natural snowfall but also limit the ability to manufacture snow), spring, summer and autumn activities might see rising popularity as the shoulder and traditional high (summer) seasons extend in length. This presents considerable risk to the winter sports sector – particularly those activities for which snowmaking is irrelevant (e.g., ice-fishing), has never been feasible (e.g., cross-country skiing) or in the case of downhill ski operations which have chosen not to or are simply financially unable to invest in snowmaking equipment. However, considerable opportunities might also present themselves in terms of providing for other activities in the lengthening spring-summer-fall. Ski areas, for example, are often the perfect venues for spring-summer-fall activities such as hiking, mountain biking, and alpine slides. These opportunities include the potential for new businesses which focus on the kinds of activities typical of this season, as well as the potential for existing businesses to diversify their offerings, whether in terms of the activities offered and/or the timing of those offerings. In both cases – new businesses and diversified existing businesses – considerable capital will likely be required, in addition to the knowledge and skills necessary to provide new and different activities safely and effectively. These needs are problematic given the characteristics typical of the small, family owned and operated enterprises that make up the majority of ORT providers throughout the Midwest region, including limited resources (capital, training, etc.) and a traditional lack of long-term planning, both of which limit adaptive capacity. In addition, experience has shown somewhat of a lack of concern for CVC as a pressing issue among many ORT providers, with rationales for this lack of concern including that CVC is too distant of an issue to be concerned with, especially in light of the current economic climate; that the jargon associated with CVC is too confusing for providers to fully understand; and that the uncertainty associated with CVC is too excessive to warrant genuine concern (Nicholls & Holecek, 2008).

The topic of adaptation has received less attention in the literature to date than impacts and implications. Nevertheless, it is clear that adaptation is a context-specific concept, meaning that to be successful adaptation measures will need to be developed in light of the activity and geographic locale under consideration. For example, Figure 8 represents a suite of suggested adaptation strategies for the downhill ski sector in the European Alps (Bürki, Abegg & Elsasser, 2007). Under the 'maintain ski tourism' option, it is immediately clear that for the Midwest, the development of slopes on higher terrain is an unlikely option, since most slopes in this part of the world are already developed on the highest terrain available. The provision of subsidies to the ski industry also seems an unlikely proposition in a US context. The 'alternatives to ski tourism' identified seem to offer more promise; though, as noted above, diversification into a year-round entity and the provision of alternative activities (e.g., the construction of a conference center so as to appeal to year-round business travelers, the construction of a spa to appeal both year-round and on rainy or snow-free days, or the development of a golf course or a water park for summer usage) are all capital-intensive investments. Interestingly, anecdotal as well as preliminary research suggests that in the case of winter operators, the more prominent rationale for diversification is not as a means of adapting to observed or anticipated CVC, but as a financial measure (McManus & Bicknell, 2006).

Temporal diversification and the potential lengthening and strengthening of the current shoulder (spring and fall) seasons raises the issue of the extent to which the availability of free time influences ORT behavior. Studies of leisure activity in Michigan have consistently identified the availability of free time, as measured by the timing of weekends and holidays, as the single most important indicators of general leisure travel, as well as participation in specific activities such as skiing and golf (Nicholls, Holecek & Noh, 2008; Shih, Nicholls & Holecek, 2009; Shih & Nicholls, 2011). The existence of more attractive conditions for ORT activity are insufficient to generate additional activity in and of themselves – potential participants must also have the time to do so.

The timing of longer windows of leisure time, most typically determined by the distributions of school summer holidays, represents an additional temporal constraint. Increased climatic attractiveness and the availability of wider selections of activities in which to engage during spring and fall would only benefit those able to take time to engage in ORT in what are currently the shoulder seasons. The trend towards year-round school in some areas, with an increased number of shorter breaks distributed throughout the year (versus the current trend of one long summer break and a limited number of short breaks over holidays), could benefit ORT providers in a warming world.

The National Park Service (NPS) recognizes the threats associated with climate change via its *Climate Friendly Parks* program (http://www.nps.gov/climatefriendlyparks). Table 4 lists the sites managed by the NPS throughout the Midwest region; sites that have been designated as "Climate Friendly" are highlighted with an asterisk. "Climate Friendly" NPS sites engage in a range of mitigation measures designed to reduce their contribution to greenhouse gas emissions.

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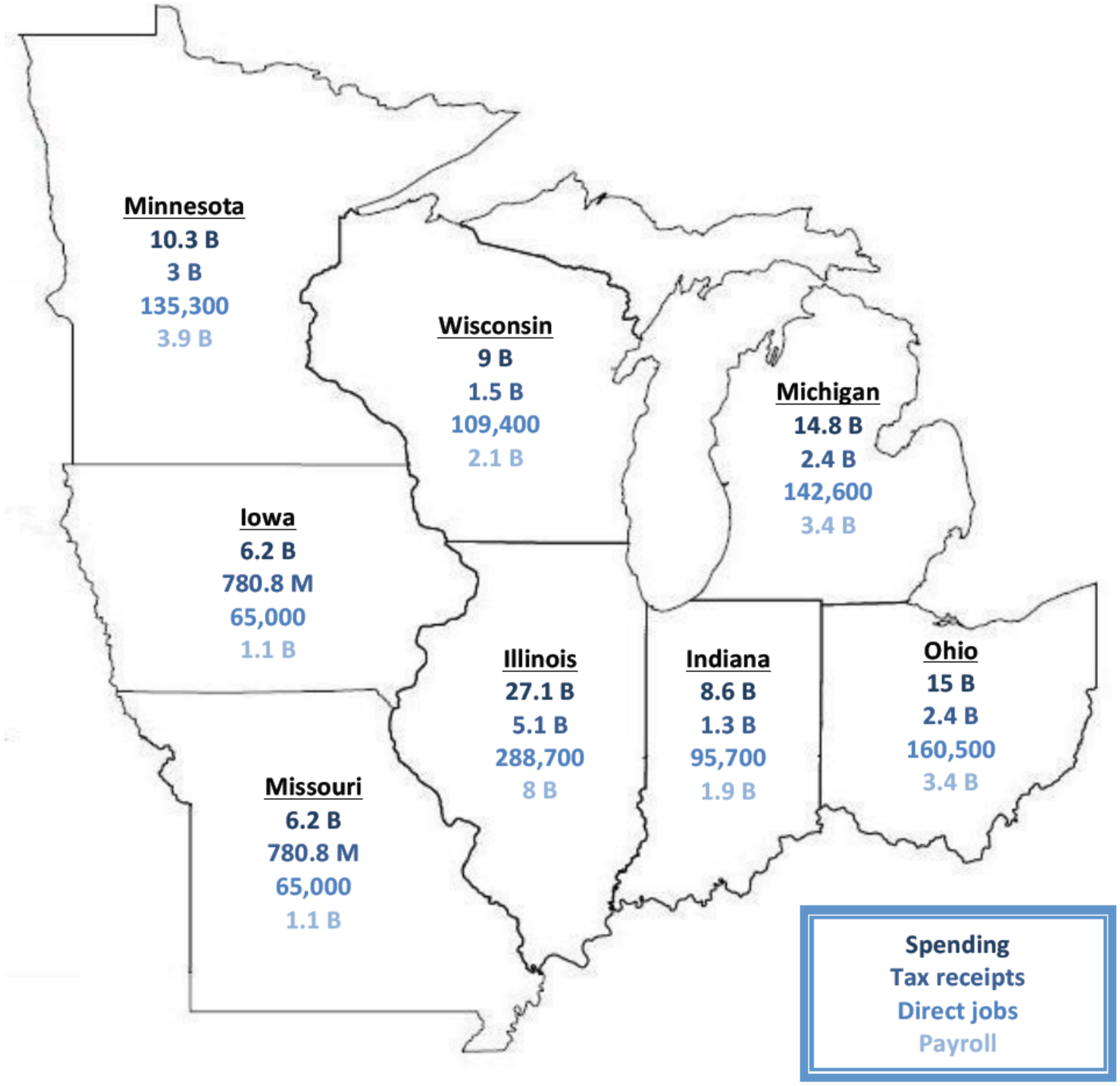
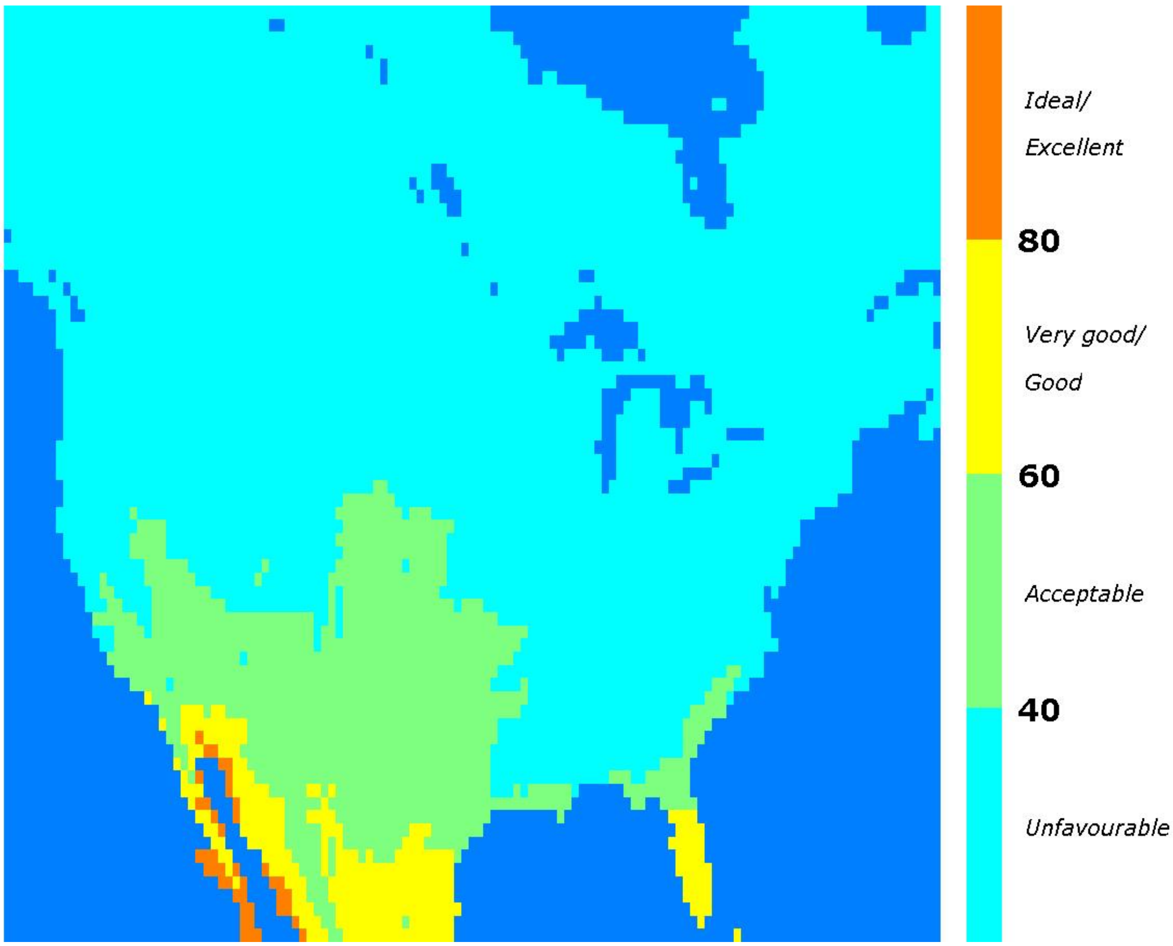
Figure 1. Contribution of Travel and Tourism to the Midwest States' Economies



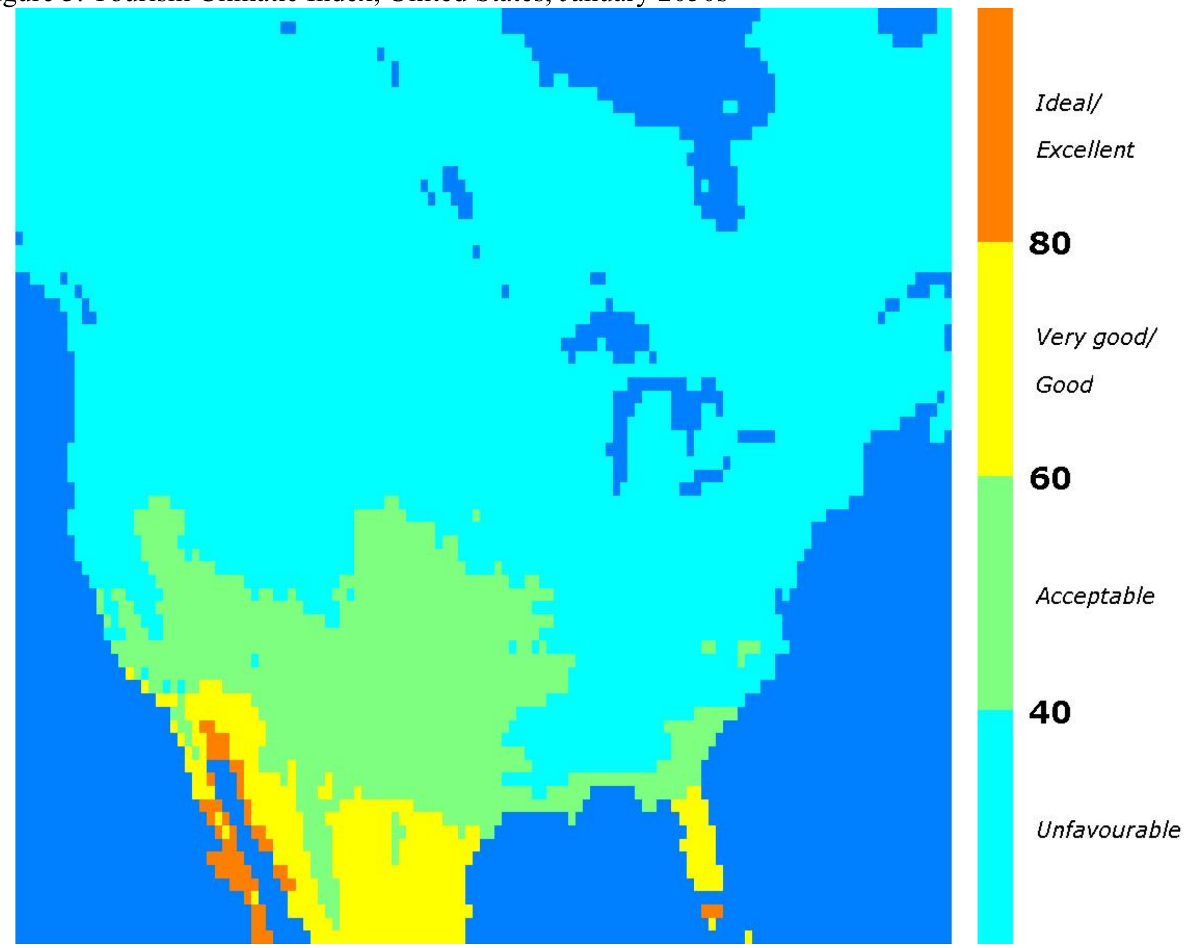
Source: U.S. Travel Association, 2012.

Figure 2. Tourism Climatic Index, United States, January 1970s



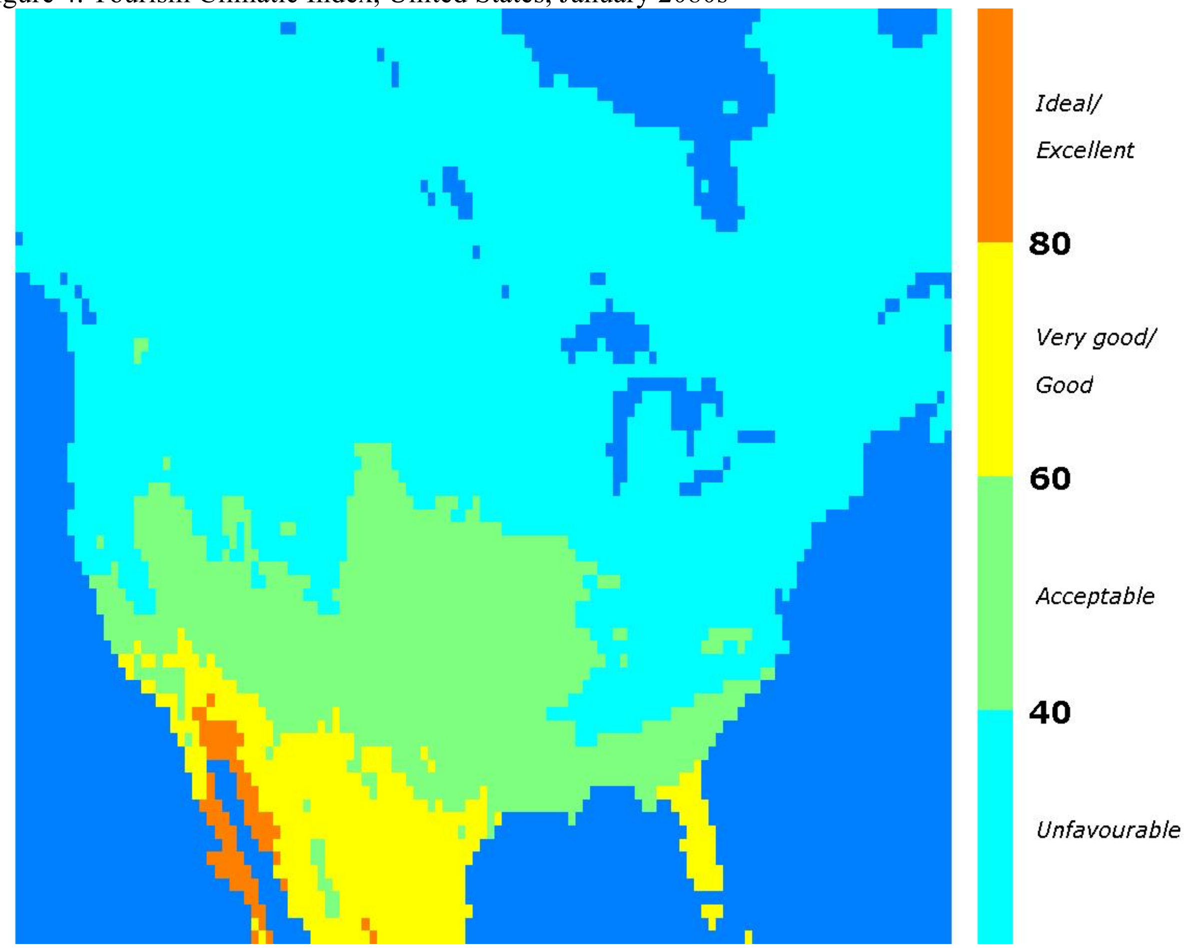
Source: Nicholls, Amelung & Viner, 2005.

Figure 3. Tourism Climatic Index, United States, January 2050s



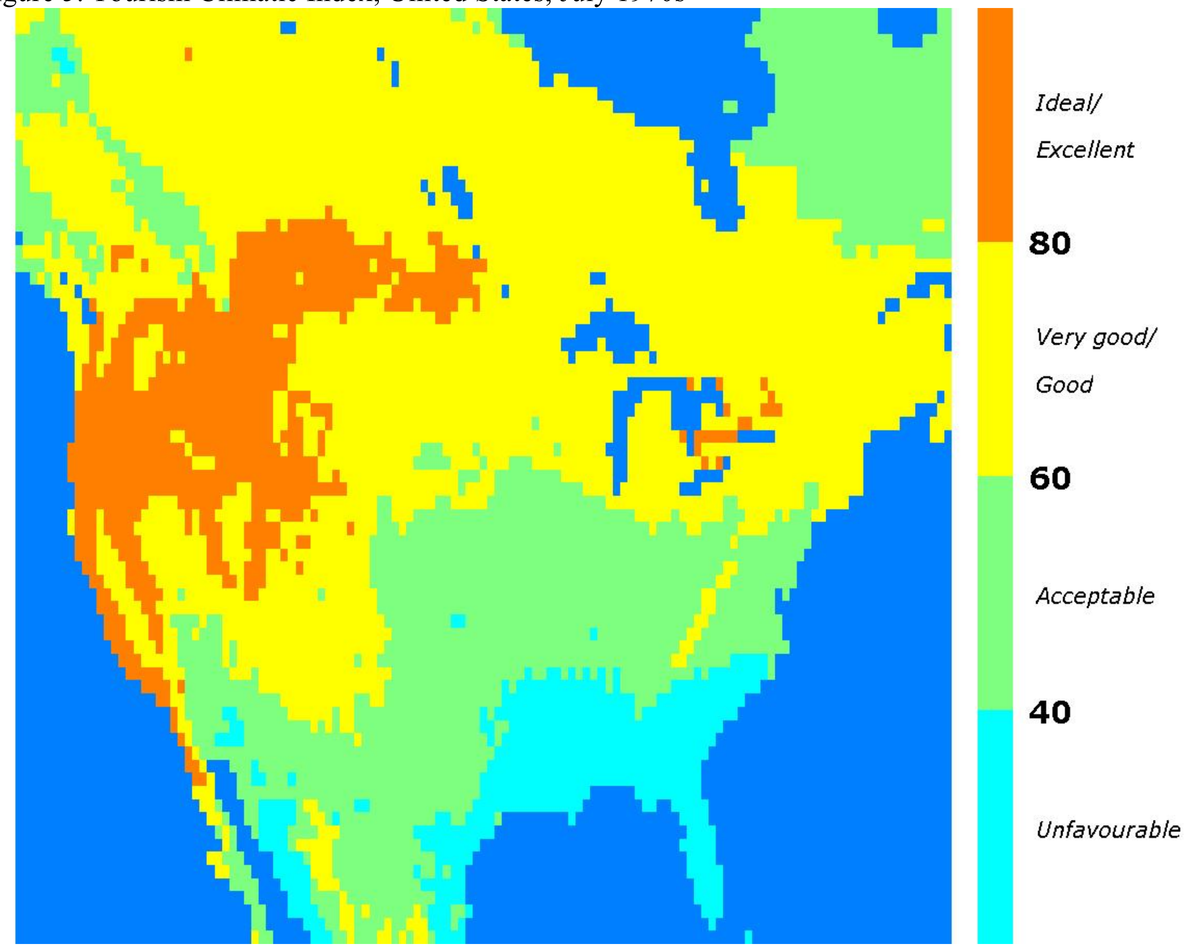
Source: Nicholls, Amelung & Viner, 2005.

Figure 4. Tourism Climatic Index, United States, January 2080s



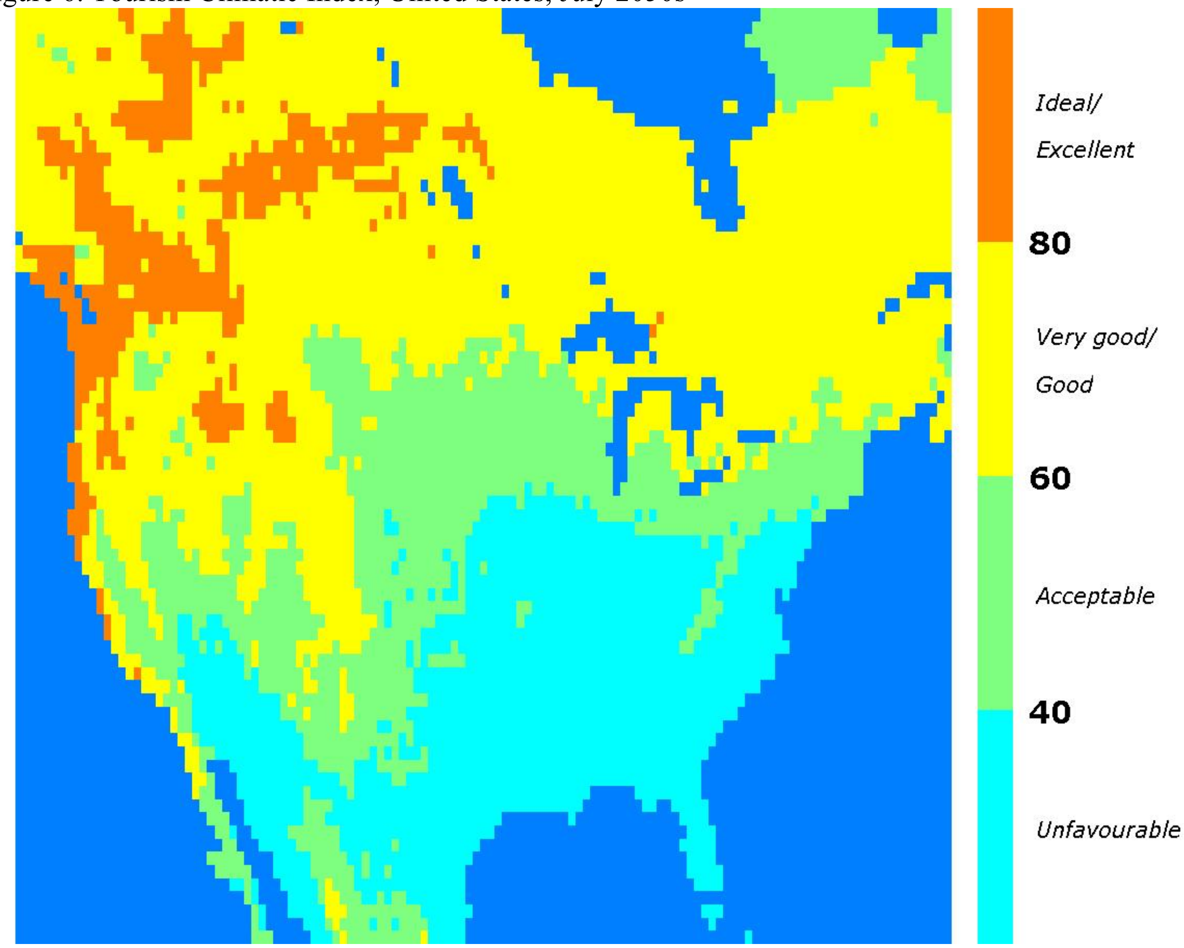
Source: Nicholls, Amelung & Viner, 2005.

Figure 5. Tourism Climatic Index, United States, July 1970s



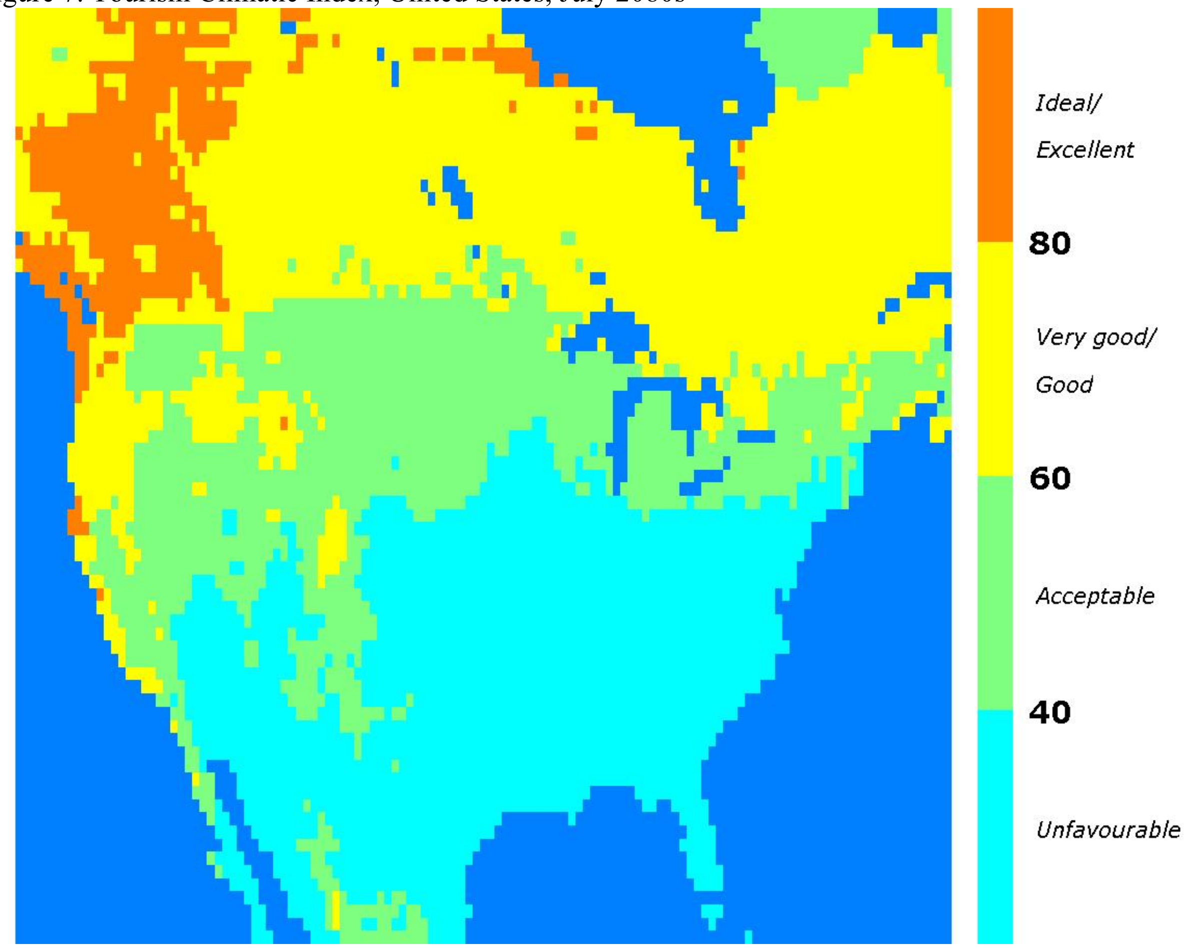
Source: Nicholls, Amelung & Viner, 2005.

Figure 6. Tourism Climatic Index, United States, July 2050s



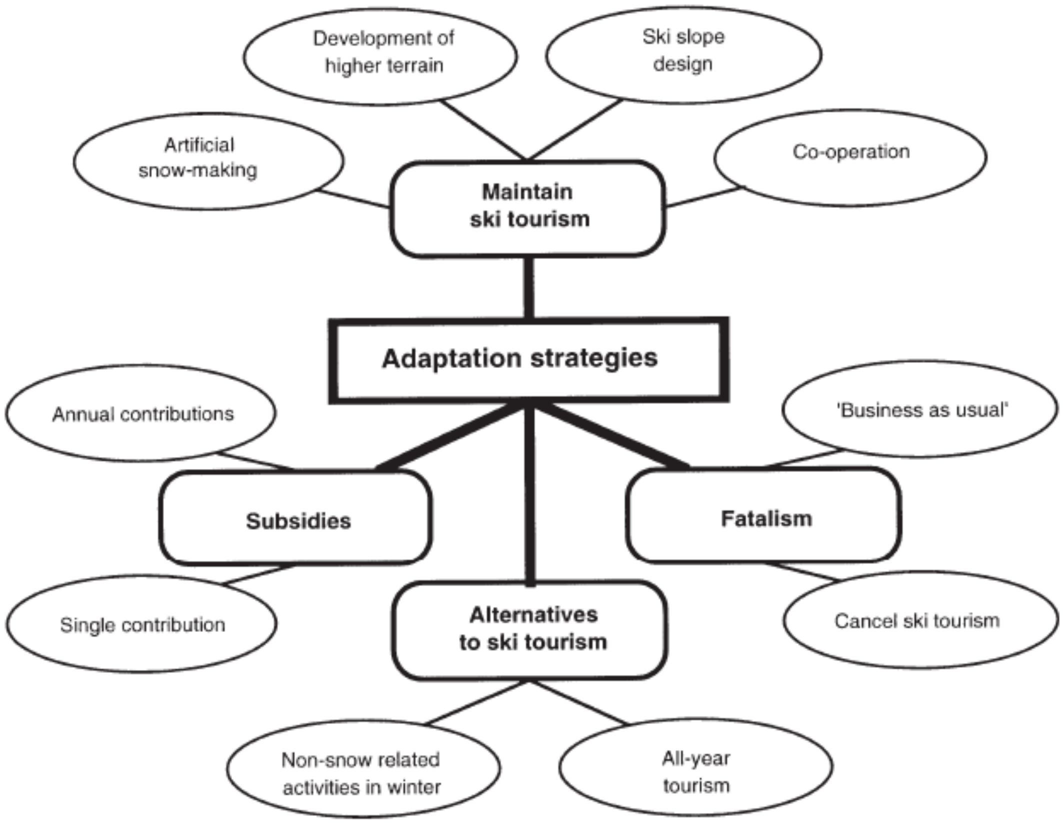
Source: Nicholls, Amelung & Viner, 2005.

Figure 7. Tourism Climatic Index, United States, July 2080s



Source: Nicholls, Amelung & Viner, 2005.

Figure 8. Potential Adaptations to Climate Change in the European Ski Sector



Source: Bürki, Abegg & Elsasser, 2007.

Table 1. Projected Climate Changes, and Potential Implications for ORT, in the Midwest

Projected Change	Potential Implications
Warmer winters with less natural snow and ice	Some activities are directly dependent on sufficiently cold temperatures to generate natural snow or ice, e.g., cross country skiing, ice fishing, snowmobiling. Without natural snow or ice, these activities may become impossible. Other activities, i.e., downhill skiing, rely on a combination of natural and manufactured snow. The ability to make snow will depend on the continuance of sufficiently cool temperatures for this activity. The threat of CVC to the Midwest's winter sports and tourism sectors is high.
Warmer springs and falls	Warmer springs and falls would likely increase the climatic attractiveness of the Midwest as an ORT venue for activities such as camping, boating and kayaking in these seasons. Certain activities are already available on a year-round basis and the settings for those activities are prepared for visitation in any season, e.g., national and state parks, whereas commercial enterprises may require restructuring to enable them to offer year-round service to ORT participants. For example, lengthening of the spring/fall seasons will have implications for staffing (especially summer activities which currently rely on student labor that will be unavailable outside of school holiday months).
Warmer summers and an increase in the frequency of heat waves	Warmer summers may sound attractive to the typical ORT participant. However, thresholds beyond which ORT activity becomes unattractive due to excess heat remain to be identified and their implications assessed. Warmer summers may place additional constraints on providers in both urban and rural settings, e.g., urban properties may be required to considerably increase their energy usage due to increased air conditioning demands, while smaller rural properties that currently do not offer air conditioning may be forced to install such technology so as to remain competitive in the marketplace. Excessive heat would likely reduce demand for camping facilities.
More frequent and/or more severe extreme weather events	Extreme weather events such as heat waves and storms have direct and indirect implications for ORT activity. Direct implications include the safety of ORT participants due to high winds, flooding, lightning, etc., and the disruption of participation in activities (e.g., having to exit the golf course during a thunder storm) and of actual or planned travel, (e.g., the delay or cancellation of flights, the closure of bridges, etc.). Severe storms and flash flooding might threaten resources such as visitor centers, archaeological sites and trails. Severe weather events might also have implications for the quality and/or aesthetics of the natural environment, thereby indirectly impacting the ORT experience.

Sources: Hayhoe, VanDorn, Croley II, Schlegal & Wuebbles, 2010; Wuebbles, Hayhoe & Parzen, 2010; Kunkel, 2011.

Table 2. Tourism Climatic Index (TCI) Rating System

90 – 100	Ideal
80 – 89	Excellent
70 – 79	Very good
60 – 69	Good
50 – 59	Acceptable
40 – 49	Marginal
30 – 39	Unfavorable
20 – 29	Very unfavorable
10 – 19	Extremely unfavorable
Below 9	Impossible

Source: Adapted from Mieczkowski (1985, pp. 228-29).

Table 3. Ski Areas in the Midwest States

State	Number of Ski Areas	Percent of US Ski Areas
Illinois	6	1.2%
Indiana	2	0.4%
Iowa	4	0.8%
Michigan	43	8.9%
Minnesota	17	3.5%
Missouri	2	0.4%
Ohio	6	1.2%
Wisconsin	10	2.0%
Total	90	18.4%

Source: National Ski Areas Association, 2011.

Table 4. National Park Service Sites in the Midwest

State	National Park Service Site
Illinois	Lewis & Clark National Historical Trail*
	Lincoln Home National Historic Site
	Mormon Pioneer National Historic Trail
	Trail of Tears National Historic Trail
Indiana	George Rogers Clark National Historical Park
	Indiana Dunes National Lakeshore*
	Lincoln Boyhood National Memorial
Iowa	Effigy Mounds National Monument
	Herbert Hoover National Historic Site
	Lewis & Clark National Historic Trail*
	Mormon Pioneer National Historic Trail
	Silos & Smokestacks National Heritage Area
Michigan	Isle Royale National Park
	Keweenaw National Historical Park
	Motor Cities National Heritage Area
	North Country National Scenic Trail
	Pictured Rocks National Lakeshore*
	Sleeping Bear Dunes National Lakeshore*
Minnesota	Grand Portage National Monument
	Mississippi National River and Recreation Area*
	North Country National Scenic Trail
	Pipestone National Monument
	Saint Croix National Scenic River
	Voyageurs National Park*
Missouri	California National Historic Trail
	George Washington Carver National Monument
	Henry S. Truman National Historic Site
	Jefferson National Expansion Memorial
	Lewis & Clark National Historic Trail*
	Oregon National Historic Trail
	Ozark National Scenic Riverways
	Pony Express National Historic Trail
	Santa Fe National Historic Trail
	Trail of Tears National Historic Trail
	Ulysses S. Grant National Historic Site
	Wilson’s Creek National Battlefield

Ohio	Cuyahoga Valley National Park David Berger National Memorial Dayton Aviation Heritage National Historical Park First Ladies National Historic Site Hopewell Culture National Historical Park James A. Garfield National Historical Site National Aviation Heritage Site North Country National Scenic Trail Perry's Victory and International Peace Memorial William Howard Taft National Historic Site
Wisconsin	Apostle Islands National Lakeshore* Ice Age National Scenic Trail* North Country National Scenic Trail Saint Croix National Scenic River

*Indicates official "Climate Friendly Park"

Climate Change Impacts on Transportation in the Midwest
John Posey

This paper assesses current literature on potential impacts of climate change on transportation systems in the Midwestern region of the United States. Four sections follow: First, a brief synopsis of recent research on transportation impacts in general is offered. Second, we examine current climate projections for different parts of the Midwest in order to assess relative levels of risk for transportation impacts associated with climate change. Third, an assessment of ongoing transportation adaptation measures is presented. Finally, gaps in knowledge and research needs are discussed.

1. Transportation and Climate Change

Changes in temperature and precipitation associated with climate change can have different effects on different modes of transportation. Summaries of these effects may be found in Jaroszweski, Chapman and Petts (2010), Koetse and Rietveld (2009), Meyer and Weigel (2011), Meyer, Amekudzi and O'Har (2010), the Panel on Adapting to the Impacts of Climate Change (PAICC, 2010), Hodges (2011) and Schwartz (2011). This section briefly summarizes current thought on ways in which climate change may affect the following modes of transportation: surface transportation (i.e., roads and highways), rail, water and air.

1.1 Air

1.1.1 Temperature change: Changes in temperature can affect takeoff performance and cargo capacity. Generally, warmer temperatures reduce the amount of lift generated by the wing of an airplane, which reduces the aircraft's carrying capacity and increases the time required to achieve a given altitude. However, there is little knowledge about the extent to which temperatures are the limiting factor in cargo capacity or takeoff performance.

1.1.2 Precipitation change: Changes in precipitation can affect air traffic in several ways. Heavy precipitation can overwhelm airport drainage systems and inundate runways, particularly for airports built in floodplains or other low-lying areas. An increase in the frequency of heavy precipitation events could therefore lead to more airport closures. In addition, heavy precipitation can degrade aviation system operations, resulting in delayed takeoffs and landings.

1.1.3 Fire: Wildfire can disrupt air traffic by reducing visibility and by degrading engine performance. Places experiencing an increase in hotter and dryer conditions may be more susceptible to wildfire.

1.1.4 Extreme weather: Tornadoes, severe thunderstorms and heavy wind can halt airport operations, and in some cases cause physical damage to airport facilities.

1.2 Water

River traffic can be disrupted by high water levels caused by heavy precipitation. Changes in the frequency of heavy and prolonged precipitation may therefore reduce the volume of river barge traffic. On the other hand, falling water levels in the Great Lakes have reduced the carrying capacity of cargo vessels in recent years, and climate change could exacerbate this trend.

1.3 Rail

1.3.1 Temperature change: Rising temperatures may lead to material stress, including buckled rails.

1.3.2 Precipitation change: Increases in heavy precipitation events could flood low-lying tracks, forcing temporary closure of low-lying rail lines.

1.4 Surface transportation:

1.4.1 Temperature change: Increases in temperature, and particularly in the frequency of extreme heat events, could increase material stress on pavement, necessitating more frequent maintenance.

1.4.2 Precipitation change: Changes in precipitation patterns could affect surface transportation in three ways. First, an increase in heavy precipitation events can lead to flooded roadways. Second, increased runoff creates faster stream currents which can erode the bases of bridges, a condition known as bridge scour. Third, precipitation generally degrades system performance, resulting in longer travel times and more crashes.

1.4.3 Extreme Weather: Tornadoes, severe thunderstorms and heavy wind can disrupt highway travel, and heavy cross winds can make long bridges unsafe. For example, the Foyle Bridge in Northern Ireland has experienced several incidents in windy conditions, and is now closed to traffic when wind speeds exceed 50 MPH.

2. Comparative risk

Current peer-reviewed literature on climate change impacts in the Midwest does not provide a basis for quantifying the costs of impacts such as material stress, flooded roadways, bridge scour and disuptions to barge traffic. However, current projections can be used to assess relative risks associated with different types of impacts in different subregions of the Midwest. The projections described in Kunkel (2011) are the basis for this section.

2.1 Extreme heat

The number of days with a temperature greater than 95 degrees is a good indicator of the risk of pavement and rail buckling. Currently, Missouri and southern Illinois are the areas of the midwest with the most days of days with a maximum temperature over 95 degrees. Western Missouri, including the Kansas City metropolitan area, experienced 40 to 50 days per year of heat over 95 degrees in the period 1971-2000. Eastern Missouri and southern Illinois were in a band that experienced 30 to 40 of these extreme heat days each year.

NARCCAP projections for the years 2041-2070 show an increase of more than 20 days each year for almost all of Missouri, including the Kansas City and St. Louis metropolitan areas, as well as for southern Illinois, southern Indiana, and the Cincinnati metropolitan area. Northern portions of the midwest, including the Minneapolis, Milwaukee, Chicago, Detroit and Indianapolis metropolitan areas, are projected to have increases of less than 20 days per year of 95+ heat. These projections suggest that heat stress on rail and pavement may be of particular concern in Missouri and the southern portions of Illinois and Indiana.

2.2: Changing precipitation patterns

2.2.1 Flooding risk

Takle (2010) maintains that precipitation levels in eastern Iowa have increased over the last 30 years:

> Using these tools, we see that eastern Iowa has experienced increased precipitation of 1 to 2 inches in spring (April through June) over the last 30 years. This is consistent with increases throughout the central U.S. since about 1976 (Groisman et al. 2005). There also is increased intensity of extreme events in the warm season. Groisman et al. (2005) report a 20 percent increase in the most intense 0.3 percent of precipitation events in the central U.S. over this period. By contrast, there has been a slight decrease in the frequency of light or average precipitation events (CCSP 2008). Records from Cedar Rapids (IEM 2008) show that there were 14 days from 1901 to 1950 that had three or more inches of daily total precipitation. Between 1951 and 2000, this number rose to 23 days. Over the last 113 years, annual precipitation in Cedar Rapids has increased by about 9 inches, from 28 to 37 inches. Increases have come in both the warm season and cool season, with the cool season precipitation currently being about 50 percent higher than a hundred years ago. The Cedar Rapids record agrees with the regional trend of increased precipitation since 1976, but the Cedar Rapids upward trend started much earlier. So althougn it is hard to argue that this locale's increase in annual total precipitation is due to anthropogenic effects of the last 30 years, models suggest this existing trend will continue. The increase in number of days with intense precipitation, by contrast, has increased in the latter part of the 20th century, which is consistent with changes attributable to anthropogenic effects (p. 112).

A conference held at St. Louis University in November, 2008 drew together several scientists who study climate change effects on streamflow. Although the papers presented at this conference were not peer reviewed, several agreed that flooding is becoming more frequent in the Mississippi River basin (Kriss, 2009; Pinter, 2009) or that flooding is likely to become more frequent under climate change scenarios (Wuebbles, Hayhoe and Cherkauer, 2009; Pan, 2009).

Current NARCCAP projections show a continuation of several of these trends through the middle of the 21st century. The entire Midwestern region is projected to see increases in precipitation in Winter, Spring and Fall.

Moreover, the number of days with more than 1 inch of precipitation is projected to increase throughout the Midwest. NARCCAP simulations for the period 1971-2000 indicate that most of the area south of the Missouri-Iowa border (an area extending as far as Columbus, Ohio) experienced about 6-8 days per year in which precipitation exceeded 1 inch. There were isolated sections in the Ohio River basin in southern Indiana and near the Mississippi confluence in which the total was higher, with 8-10 days per year exceeding 1 inch of precipitation. Most of the Mississippi River basin between the Iowa-Missouri border and Minneapolis saw 4-6 days per year with more than 1 inch of precipitation. NARCCAP projects an increase in heavy precipitation days for the period 2041-2070. The Mississippi River basin between the Quad Cities and LaCrosse, Wisconsin is projected to see an increase of 3-4 days every two years, while the rest of the basin between St. Louis and Minneapolis is projected to have an increase of 2-3 days every two years.

These projections suggest an increased risk of disruptions to navigation on the Ohio, Mississippi and Missouri Rivers. In addition, the projected increase in heavy precipitation throughout the Midwest suggests additional risk of temporary flooding of rails and roadways.

The observations and projections cited above do not appear to contradict the opinion of Pryor, Kunkel and Schoof (2009) that "the most common cause of flooding is intense and/or prolonged storm precipitation (Nott, 2006). Given the increase in intensity of extreme precipitation events, an increased risk of flooding seems likely."

2.2.2 Snow

NARCCAP projections indicate rising winter precipitation over much of the Midwest, suggesting a rising risk of transportation system disruption caused by snow and ice. Monitoring changes in snow removal budgets may be one simple and effective adaptation option that can be taken by state and local transportation authorities.

2.3: Great Lakes water levels

Wang et al. (2010) report that water levels on the Great Lakes dropped in the 1990s, resulting in significant transportation impacts in the Great Lakes region:

> From the late 1990s to the early 2000s, the volume of lake ice cover was much lower than normal, which enhanced evaporation and led to a significant water level drop, as much as 1.3 meters. Lower water levels have a significant impact on the Great Lakes economy. For example, more than 200 million tons of cargo are shipped every year through the Great Lakes. Since 1998--when water levels took a severe drop--commercial ships have been forced to lighten their loads; for every inch of clearance that these oceangoing vessels sacrificed due to low water levels, each ship lost US$11,000-22,000 in profits.

There is considerable uncertainty regarding future water levels on the Great Lakes. Angel and Kunkel (2010) report that an output of 565 model runs from 23 Global Climate Models were applied to a lake-level model. Under the A2 scenario, median chnges in lake levels were -.41 meters; under B1, the median drop was -.25 meters. However, the range in lake levels projected by the various models was considerable, leading to high uncertainty about future lake levels.

Hayhoe et al. (2010) note that expected increases in precipitation may offset increases in temperature, leading to uncertainty about water levels, at least by the middle of the 21st century: "Competing effects of shifting precipitation and warmer temperatures suggest little change in Great Lake levels over much of the century until the end of the century, when net decreases are expected under higher emissions."

The Wisconsin Initiative on Climate Change Impacts (WICCI) 2011) notes that the Great Lakes have historically experienced both high water and low water decades. According to WICCI, climate change could potentially create both high and low water decades that exceed normal decadal variations. The report suggests that ports and marinas may need to take the possibility of greater fluctuations into account when designing and building new infrastructure. In addition, WICCI posits that lower water levels could force cargo vessels to carry lighter loads.

According to Cruce and Yurkovich (2011), "Great Lakes shipping is very sensitive to lower lake levels as an annual mean or during periods of seasonal variation." A 1,000 foot vessel loses 270 tons of capacity per inch of lost draft, which equates to about $30,000. Low water levels between 1997 and 2000 forced shippers to reduce cargo tonnage by 5% to 8%. According to Cruce and Yurkovich, research conducted by Millerd (2007) at Wilfrid Laurier University indicates that falling water levels are expected to increase operating costs by 1.9% to 7.4% by 2030, with costs projected to rise to between 13.3% and 26.7% by the end of the century. Subsequent research by Millerd (2011) places the estimated cost at between 5% and 22% by 2030.

Cruce and Yurkovich argue that falling water levels could also damage port and marina infrastructure, and increase dredging costs. They note that less ice on the St. Lawrence Seaway could present opportunities to shippers; since the 1980s, the annual amount of time in which the seaway is closed because of ice has dropped by about 10 days per year.

A reduction in lake ice may partially offset some of the challenges associated with varying water levels. Warmer conditions, reducing lake ice, could result in more navigable days, which would benefit shippers.

3. Ongoing adaptation efforts

3.1 Chicago: The City of Chicago has a Climate Action Plan (CAP) (City of Chicago, 2008). Most of the plan focuses on mitigation efforts. In particular, most of the plan elements related to transportation emphasize greenhouse gas reduction, including measures to promote transit-oriented development and alternative modes of transportation. However, the CAP explicitly addresses climate change impacts on transportation, noting that an increasing frequency of heavy precipitation events is likely to result in traffic delays and damage to infrastructure.

The bulk of adaptation measures related to transportation in the Chicago CAP involve stormwater management. The CAP calls for increased use of permeable paving surfaces, rain gardens, rain barrels and landscaping to reduce storm runoff. The City's Green Urban Design (GUD) plan includes measures to modify alleys to reduce runoff, and dozens of alley modifications have been implemented thus far.

3.2 Wisconsin: The Wisconsin Initiative on Climate Change Impacts (WICCI) released a report in 2011. The report addresses potential impacts on both surface transportation and water transport.

The report anticipates an increase in the frequency of transportation infrastructure damage and temporary flooding as a result of more frequent incidents of heavy rain.

The WICCI report highlights 2008 flooding on the Baraboo River as an example of vulnerability to high water conditions. According to the report, "the Wisconsin Department of Transportation is conducting a review of the vulnerability of the entire interstate highway system as a result of flood-triggered closures of I-39, I-90, and I-94 at the Baraboo River in Columbia County. Engineers will weigh the costs of flood-proofind stream crossings and embankments against the economic costs of temporary closures...."

In addition to stormwater impacts, the WICCI report also notes the need for additional research on potential material stress. In particular, WICCI suggests that projections of changes in freeze-thaw cycles could be used to predict changes in the useful life of concrete, with maintenance measures adjusted accordingly.

As in the Chicago CAP, the major adaptation elements related to transportation in the WICCI plan are those that address stormwater runoff. WICCI recommends open space preservation, Low Impact Design (LID) methods for paved surfaces, and green roofs to reduce runoff.

3.3 Iowa: The Iowa Climate Change Impacts Committee (ICCIC) was formed by an act of the Iowa General Assembly. In January, 2011, the ICCIC issued a report on potential climate change impacts for Iowa.

The ICCIC report indicates that precipitation in Iowa has increased over the last 100 years, and that the number of intense rain events has also increased. The report further asserts that certain places such as Cedar Rapids have seen greater increases than the state as a whole. In addition, the report states that streamflows have risen in recent years, and reports that streamflow projections conducted by researchers at Iowa State University indicate that increased precipitation could result in a 50% increase in streamflow in the Mississippi River basin. ICCIC concludes that these findings suggest that the risk of flooding is rising.

The report does not focus extensively on the relationship between climate change and transportation infrastructure, but does note that higher temperatures increase the risk of road buckling, and that increased precipitation and stream flow would increase the risk of washed out roads and bridges.

3.4 Michigan Department of Transportation. MDOT has conducted an analysis of potential challenges related to climate change, and has developed a menu of potential responses. MDOT staff presented their analysis at an April 7 2011 webinar conducted by the Transportation Research Board of the National Academies (Johnson, 2011).

The main areas of concern for MDOT are the possibility of more intense storms and hotter, drier summers. Methods for adapting to more intense storms include using larger hydraulic openings for bridges, armoring of ditches to prevent erosion, installation of higher capacity pumps to ensure that drainage systems are not overwhelmed, and use of intelligent transportation systems (ITS) that help motorists adapt to changing traffic conditions. Methods for adapting to hotter and drier summers include intensifying monitoring of pavement conditions during extreme heat periods and encouraging more night work to prevent premature cracking.

3.5 Federal Highways Administration (FHWA): FHWA is undertaking at least two initiatives to help Midwestern states prepare for challenges associated with climate change. These include updated flood frequency hydrographs and peer learning events.

3.4.1 Precipitation Frequency Analysis: State departments of transportation use precipitation frequency graphs to develop design standards for culverts and other hydraulic structures. These design standards are promulgated by a state DOT to ensure that adequate drainage capacity exists for roads built in the state. Basing design standards on current precipitation frequency data is an important adaptation measure because using updated information reduces the risk of road closures or infrastructure damage due to heavy precipitation. Unfortunately, in some parts of the country, rainfall maps have not been updated for decades.

FHWA is currently conducting a pooled fund program through which state DOTs can contribute funds to update precipitation estimates (Transportation Pooled Fund Program, 2011). In the Midwest, contributors to the pooled fund include the transportation departments of the following states: Colorado, Iowa, Kansas, Minnesota, Missouri, Nebraska and South Dakota. The study uses updated information from NOAA to determine annual exceedance probabilities (AEP) and average recurrence intervals (ARI) for durations ranging from 5 minutes to 60 days and for ARIs from 1 to 1,000 years. Point estimates will be spatially interpolated to a spatial resolution of approximately 4km x 4km.

3.4.2 Peer Learning:

FHWA hosts peer learning events for Metropolitan Planning Organizations (MPOs) and state departments of transportation. An exchange held in May, 2011, included MPOs and DOTs from the Midwest.

The final report from these sessions includes from state and local planning officials (ICF International, 2011). Representatives from MPOs identified county hazard mitigation planning efforts as a vehicle for climate change adaptation planning. Barriers to adaptation include the lack of inter-agency collaboration and the lack of localized climate data.

The state DOT session focused on the possibility of more frequent heavy precipitation events, which could cause more bridge scour, and which could also make current culverts and drainage systems inadequate. Presenters stated that more frequent incidents of heavy precipitation could overwhelm drainage systems, leading to an increased risk of roadway flooding.

One presenter argued that an asset management approach to infrastructure maintenance and design should be considered an effective adaptation measure. Transportation asset management consists of continually monitoring the condition of assets such as roads, bridges and culverts using geographic information systems and other tools. Assets considered critical to system performance are identified, as is the required level of service. These considerations inform investment strategies and long-term funding strategies.

By conducting peer exchanges such as these, FHWA is providing technical assistance to state and local planners who will be making adaptation decisions for transportation systems. Transportation asset management and integration with hazard mitigation plans are two useful ideas to come from the Indianapolis sessions.

4. Research needs

Three main research needs emerge from the foregoing summary. First, there is a need to quantify impacts of climate change on transportation for the Midwest region, and for specific communities in the Midwest. Second, there is a need to model the effectiveness of adaptation options. Third, there is a need to integrate uncertainty into decision making about adaptation options.

4.1 Quantifying impacts

Although there is a qualitative understanding of the types of impacts that might exist under climate change scenarios, there is little peer-reviewed literature that quantifies transportation impacts in the Midwest. The area of Midwestern transportation that has had the most quantitative analysis has been Great Lakes shipping, where researchers have been able to measure likely changes in cargo capacity due to falling water levels.

Analysis at this level has not been performed for surface transportation or rail in the Midwest. For example, it is reasonable to conclude that an increase in 95+ degree days will increase material stress on pavement and rail. A useful next step would be to quantify the potential damage in terms of a pavement condition index, useful life or cost of maintenance.

To pick another example, it is reasonable to expect that flooding of roadways may increase due to changing precipitation patterns. But it would be useful to quantify the impacts in terms of vehicle miles of travel (VMT) or vehicle hours of travel (VHT). Tallying the cost of lost shipping days on the Ohio and Mississippi Rivers would also be of benefit.

4.2 Adaptation effectiveness.

There is now a rich literature on adaptation measures being undertaken. But there is a strong need for additional work that models the effectiveness of different adaptation options. In particular, there is a widespread understanding of the connection between stormwater management and transportation, with a realization that reducing runoff can also reduce flooding on roadways. Needed is a way to measure the effectiveness of different options. Modeling the effectiveness of different options, including permeable paving surfaces, open space preservation and rain gardens, would allow a more robust cost-benefit analysis, which would inform policy and planning at the local level.

4.3 Uncertainty

The presence of uncertainty raises serious problems for decision makers. The issue of water levels on the Great Lakes is a good example. There is much uncertainty about future water levels, and there is even a possibility that water levels could rise during some years of the next century. Given the uncertainty, how can decision makers determine optimal adaptation strategies?

An approach to risk management known as Robust Decision Making (RDM) has entered the literature on transportation and climate change. The concept was introduced to the study of climate change adaptation by Lempert and Schlesinger (2000), who drew a distinction between prediction-based approaches and "robust" approaches to risk management. Predictive approaches attempt to determine the most likely scenario, and to design a management response that optimizes outcomes under a specified condition. By contrast, the RDM approach is useful for situations in which there is "deep uncertainty" about future conditions. In such a situation, according to Lempert and Schlesinger, the best solution will be one that provides acceptable outcomes across a wide range of possible scenarios. In RDM, the use of mathematical models to project outcomes under different scenarios is a key tool.

Schwartz (2011) applies this approach to the study of transportation adaptation, arguing that robust strategies "encompass structural, operational, and institutional options." Schwartz describes RDM as an approach that incorporates multiple views of the future, uses robustness across multiple scenarios rather than optimization as a decision criterion, and allows iterative ability to assess and adjust to vulnerabilities. Schwartz uses as an example a coastal community facing a rise in sea level and storm surge. Even if a reasonable degree of confidence exists with respect to the long term trend, the timing and amount of sea level rise remains highly uncertain. In this situation, the most robust strategy may not be to simply retrofit all existing assets. Rather, a more cost-effective approach may be to continually monitor changing conditions, rebuilding only critical assets when sea levels reach a critical height.

Another example of a possible application of RDM to transportation planning is the uncertainty over water levels in the Great Lakes. Although many models project falling water levels, the range of projections is so great that it would be risky to make major investment decisions based on optimization for a single scenario. Given the deep uncertainty, it may be rational for designers of ports, marinas, and perhaps even cargo vessels to consider performance across a range of possible water levels. Additional research on performance of adaptation measures across a range of scenarios would give policy makers the tools with which to evaluate proposed options.

5. Conclusions

Following is a summary of key impacts, with an assessment of the level of confidence associated with each.

Medium Confidence:

- There is a rising risk of disruption of Mississippi River navigation. Given that flooding impacts are already significant, have grown in recent decades, and are projected to continue growing, the assignment of medium confidence to these impacts seems reasonable.
- There is a rising risk of temporary flooding of roads and rails due to both riverine flooding and ponding. This assessment is based on recent increases in the frequency of intense precipitation

events, projected increases in the frequency of intense precipitation events and projected increases in winter and spring precipitation in the Mississippi River basin.

- There is a rising risk of disruption to Great Lakes navigation due to variability in water levels. Recent economic impacts of falling water levels have been well documented, and projections indicate that variability is likely to increase over the next century.

Low Confidence:

Although it is reasonable to hypothesize that the following impacts may occur, there is currently insufficient quantitative data with which to assess the likely severity of these impacts:

- Warmer air temperatures and increased frequency of extreme weather and heavy winds may disrupt air traffic.
- Warmer temperatures may increase heat-related stress on pavements and rails.
- Faster stream currents caused by an increase in heavy precipitation events may result in increasing severity of bridge scour, which could affect both rail and highway travel.

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Focus: Midwestern Levees

John Posey

Introduction

Levees are critical infrastructure, protecting homes, farms, factories and commercial establishments. There are more than 3,700 linear miles of federal levees in the Midwest region, protecting some 7 million acres of land (U.S. Army Corps of Engineers, 2012). A levee failure can be catastrophic to a community. The National Committee on Levee Safety (NCLS) (2011) offers several examples of recent levee failures in the Midwest:

- During the Great Flood of 1993, 40 federal levees were either overtopped or damaged.
- In 2008, flood waters overtopped levees in Cedar Rapids, Iowa, inundating several municipal buildings, as well as 3,900 homes. The town of Oakville, Iowa was devastated when its levee failed, with every building in town damaged. As a result, more than two thirds of its population subsequently moved away.
- Also in 2008, the Indiana communities of Munster and Hammond were flooded after a levee on the Little Calumet River breached, leading to a Presidential disaster declaration.
- In 2011, a levee five miles south of Hamburg, Iowa breached in three locations, leading to the eventual collapse of the levee.
- In 2011, levees on the Black River in Missouri were overtopped 30 times, with levee breaches occurring four times.

Levee Condition

In recent years there have been indications that the condition of many levees is unsatisfactory. NCLS (2009) asserts that many levees were built more than 50 years ago using construction techniques that are now considered obsolete. In addition, levees originally built to protect agricultural fields now often protect densely developed urban land. As a result, according to NCLS, "many urban areas protected by levees, particularly those in deep floodplains, have an unacceptably low level of flood protection and an unacceptably high risk. Failure of such levees can result in high loss of life, property damage, and economic losses."

In 2009, the American Society of Civil Engineers (ASCE) gave the nation's levee system a grade of D-, asserting that $50 billion over five years would be required to bring levees up to acceptable levels; ASCE states that only $1.13 billion had been committed for this purpose.

The Water Resources Development Act of 2007 (WRDA) directed the U.S. Army Corps of Engineers (USACE) to conduct an inventory and inspection of all federal levees. NCLS estimates that federal levees, which are covered by WRDA, represent only about 15% of the miles of levee systems in the country. Still, many large communities along the Mississippi, Missouri and Ohio Rivers are protected by federal levees.

As of January, 2012, the USACE National Levee Database contained ratings for 1,179 linear miles of levee systems in the Midwest, with 2,520 miles unrated. Of the levee systems that had been inspected, a rating of “acceptable” was given to 74 miles of levee systems. A rating of “minimally acceptable” was given to 921 miles. A rating of "unacceptable" was given to 184 miles , about 16% of the total linear mileage (USACE, 2012).

In addition to the inspections conducted by USACE, the Federal Emergency Management Agency (FEMA) is conducting a review of levee systems as part of its Map Modernization Program (MMP). Communities that cannot provide documentation that levees are capable of providing protection against a 100 year flood face the possible deaccreditation of their levees, which can trigger a requirement to purchase flood insurance. FEMA has not released a list of levees that face deaccreditation, but Posey and Rogers (2010) estimate that the number of communities facing deaccreditation nationwide numbers in the hundreds. It should be noted that some communities are challenging deaccreditation decisions (County of Madison et al., 2011).

Increasing Flood Risk

As questions are raised about the adequacy of levees, the risk of flooding in the Mississippi River basin appears to be increasing.

NOTE TO REVIEWERS: I suspect that the following yellow-highlighted section may be rendered superfluous by the work of the water resources technical input team. If another paper offers an assessment of changes in flooding risk, then the following can be replaced with a citation of that technical input document.

Takle (2010) maintains that precipitation levels in eastern Iowa have increased over the last 30 years:

> Using these tools, we see that eastern Iowa has experienced increased precipitation of 1 to 2 inches in spring (April through June) over the last 30 years. This is consistent with increases throughout the central U.S. since about 1976 (Groisman et al. 2005). There also is increased intensity of extreme events in the warm season. Groisman et al. (2005) report a 20 percent increase in the most intense 0.3 percent of precipitation events in the central U.S. over this period. By contrast, there has been a slight decrease in the frequency of light or average precipitation events (CCSP 2008). Records from Cedar Rapids (IEM 2008) show that there were 14 days from 1901 to 1950 that had three or more inches of daily total precipitation. Between 1951 and 2000, this number rose to 23 days. Over the last 113 years, annual precipitation in Cedar Rapids has increased by about 9 inches, from 28 to 37 inches. Increases have come in both the warm season and cool season, with the cool season precipitation currently being about 50 percent higher than a hundred years ago. The Cedar Rapids record agrees with the regional trend of increased precipitation since 1976, but the Cedar Rapids upward trend started much earlier. So althougn it is hard to argue that this locale's increase in annual total precipitation is due to anthropogenic effects of the last 30 years, models suggest this existing trend will continue. The increase in number of days with intense precipitation, by contrast, has increased in the latter part of the 20th century, which is consistent with changes attributable to anthropogenic effects (p. 112).

A conference held at St. Louis University in November, 2008 drew together several scientists who study climate change effects on streamflow. Although the papers presented at this conference were not peer reviewed, several agreed that flooding is becoming more frequent in the Mississippi River basin (Criss, 2009; Pinter, 2009) or that flooding is likely to become more frequent under climate change scenarios (Wuebbles, Hayhoe and Cherkauer, 2009; Pan, 2009).

Current NARCCAP projections show a continuation of several of these trends through the middle of the 21st century (Kunkel, 2011). The entire Midwestern region is projected to see increases in precipitation in Winter, Spring and Fall.

Moreover, the number of days with more than 1 inch of precipitation is projected to increase throughout the Midwest. Between 1971 and 2000, most of the area south of the Missouri-Iowa border (an area extending as far as Columbus, Ohio) experienced about 6-8 days per year in which precipitation exceeded 1 inch.[1] There were isolated sections in the Ohio River basin in southern Indiana and near the Mississippi confluence in which the total was higher, with 8-10 days per year exceeding 1 inch of precipitation. Most of the Mississippi River basin between the Iowa-Missouri border and Minneapolis saw 4-6 days per year with more than 1 inch of precipitation. NARCCAP projects an increase in heavy precipitation days for the period 2041-2070. The Mississippi River basin between the Quad Cities and LaCrosse, Wisconsin is projected to see an increase of 3-4 days every two years, while the rest of the basin between St. Louis and Minneapolis is projected to have an increase of 2-3 days every two years.

The observations and projections cited above do not appear to contradict the opinion of Pryor and Kunkel (2009) that "the most common cause of flooding is intense and/or prolonged storm precipitation (Nott, 2006). Given the increase in intensity of extreme precipitation events, an increased risk of flooding seems likely."

Adaptation

Four adaptation options deserve consideration as the nation manages its levee system in the face of increased flooding risk. First, new development in floodplains can be discouraged. Second, buyouts can be used to encourage property owners in floodplains to move. Third, the deliberate breaching of levees is a controversial option. Finally, the rebuilding and repair of existing urban levee systems is an important task.

New development: Every new levee that is built increases pressure on existing levees. Discouraging development in floodplains that will require new levee systems is therefore a key adaptation option.

Buyouts: The acquisition of flood-prone properties has been an important tool for reducing flooding risk, and should be considered a key adaptation option. Once properties are purchased, the land is dedicated to open space, either for recreational uses or for natural wetlands. After the devastating 1993 flood, FEMA provided $54.9 million to the State of Missouri in Hazard

[1] I'm not sure if this is based on observations or NCEP-driven projections of NARCCAP models; need clarification from K. Kunkel.

Mitigation Grant Program funding. Missouri used the majority of these funds to acquire, relocate or elevate more than 4,800 properties (FEMA, 2002).

Deliberate breaching or abandonment: The breaching of agricultural levees in sparsely populated areas for the purpose of relieving pressure on levees protecting more densely populated urban areas has been a controversial flood control tactic. It was used most recently in May, 2011, near Birds Point, Missouri. According to Olson and Morton (2012):

> Heavy snow melt and rainfall ten times greater than average across the eastern half of the ... Mississippi watershed in spring and early summer of 2011 produced one of the most powerful floods in the river's known history....The deliberate breaching of the levees in the New Madrid Floodway below Cairo in May 2011 was a planned strategy to reduce water pressure and prevent levee failures where harm to human life might occur. The induced breach and the flooding of 53,824 ha (133,000 ac) of Missouri farmland resulted in the loss of 2011 crops and damage to future soil productivity.

The breaching damaged about 200 buildings, including about 90 homes. Lawsuits were filed on behalf of property owners in an attempt to stop the breach, although the authority of the U.S. Army Corps of Engineers to use the floodway was upheld.

The action at Birds Point revealed a tradeoff between protection of farmland in rural communities and protection of densely populated urban areas. Many agricultural levees were built in the 1930s, and protect sparsely populated areas. Allowing agricultural levees to be overtopped, or to be deliberately breached, is an option that allows low-lying land to be used for storage of water from overflowing rivers, relieving pressure on urban levees. However, this policy option is highly sensitive in rural areas. As flooding risks rise in coming years, difficult decisions may have to be faced regarding tradeoffs between protecting urban and rural lands, and just compensation for those affected by these decisions.

Abandoning selected rural levees for the purpose of relieving pressure on urban levees could result in significant damage to productive agricultural lands. On the other hand, removal of levees could have the additional benefit of allowing the restoration of wetlands, which have both high ecological significance and high flood control value.

Repairing urban levees: The possibility of increased flooding risk in the Midwest, combined with questions over the adequacy of levee systems protecting Midwestern communities, suggest that repair and enhancement of levee systems will be a key adaptation option in the region. Historically, the job of maintaining levee systems has included key roles for both local governments and the U.S. Army Corps of Engineers, and a partnership between federal and local agencies will remain crucial.

The Southwest Illinois Flood Protection District Council provides a model of regional collaboration to enhance levee protection. The following information is taken from the Council's Project Implementation Plan, approved July, 2011.

The Council was formed in 2009 through an Intergovernmental Agreement between the Flood Prevention Districts of Madison, St. Clair and Monroe counties as authorized by the Illinois Flood Prevention District Act of 2008 (70 ILCS 750). Voters in each of the three affected counties passed a 1/4 cent sales tax in 2008 to finance levee repairs. The tax has been collected since 2009, and produces about $11 million annually.

Five separate levee systems in the three counties protect a 174 square mile area known as the American Bottom. The American Bottom, part of the St. Louis metropolitan area, is home to about 155,000 residents; businesses in the area employ over 55,000 people. Many major manufacturing facilities are located in the area.

Leaders in the three counties banded together to enhance levee protection in the area, even though experience in previous floods, as well as past inspections, do not indicate that the levee systems would fail to protect against a 100 year flood. According to the Project Implementation Plan, the "American Bottom has not been flooded by the Mississippi River in the 70 years since the flood protection system was initially built, including during the flood of record in 1993, a 300-year event....The levee systems have consistently been determined to be in acceptable or marginally acceptable condition by annual and more thorough 3-year periodic inspections by the [U.S. Army] Corps [of Engineers]."

The Council's Project Implementation Plan outlines a five year, $150 million project to maintain the levee system's high level of flood protection. Climate change was not a factor in the decision to enhance flood protection in the American Bottom. Still, the regional collaboration that created the Council provides an illustration of how local governments can reduce risk by creating solutions across jurisdictional boundaries.

Conclusion

The projected increases in flooding risk over the next century heighten the urgency of examining the nation's levee system. Repairing urban levees that protect dense housing and heavy industry is a key adaptation option. Other potential adaptation options to be considered are protection of floodplains from further development, buying out properties currently located in floodplains, and using sparsely populated areas currently protected by agricultural levees for storage during severe floods.

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Draft White Paper—Midwest Region, Water Resources Sector

Brent Lofgren and Andrew Gronewold

February 1, 2012

1. Introduction

The water resources of the midwestern United States, and how they are managed under a future climate, have a significant collective impact on multiple sectors of the US, the North American, and the Global economy. The North American Laurentian Great Lakes, for example, hold nearly 20% of the earth's accessible surface fresh water supply and have a coastline, and a coastal population, on the same order of magnitude as frequently-studied ocean coasts around the world (Fuller et al. 1995). In light of growing demands for clean water, access to coastal resources, and an improved understanding of climate dynamics in the midwest region, a significnat amount of research has recently been focused on understanding climate impacts on the lakes (both large and small), rivers, and streams in this region. While not a specific theme of this particular assessment, we find that this region also, through explicit and implicit partnerships with the Canadian governemnt, represents an ideal testbed for establishing effective protocols for collaborative binational water resources and ecosystem services research (Gronewold and Fortin 2012). The value of the water resource management and climate change lessons to be learned from this region, however, depends on an explicit acknowledgement of those water budget components which are uncertain or unobservable (such as overlake evaporation and evapotranspiration), and how projections of regional climate dynamics are downscaled to a suitable local scale, translated into suitable water resource management metrics, and subsequently placed within an appropriate historical context.

2. Historic variability of hydroclimate

a. Seasonal to multi-year events

Pan and Pryor (2009) point out that the amount of water vapor in the atmosphere has been increasing at a greater rate in proportion to its historic values than the rate of precipitation. The total water vapor content of the atmosphere has increased in proportion to the Clausius-Clapeyron relation, i.e. it scales as an exponential function of temperature, with absolute humidity or water vapor mixing ratio increasing by about 7% per degree C. However, the mean rate of precipitation has increased by only about 2% per degree C, implying an increasing residence time of water vapor in the atmosphere. Additional theoretical consideration of this phenomenon can be found in Held and Soden (2006).

Pryor et al. (2009) have found statistically significant changes in total precipitation and number of rain days at many stations in the Midwest, mostly increases in both variables, but few stations have statistically significant change in precipitation intensity (precipitation per rain day). They also showed an increase in the amount of precipitation that came on the 10 days of the year with the greatest precipitation. However, this was not evaluated as a proportion of the total precipitation. They also found that there was generally a decrease in the mean number of consecutive days without precipitation.

Observed streamflow has shown an increasing trend since 1940 in the United States in general (Lins and Slack 1999, USGS 2005), and particularly in the Midwest region. More specifically, the streamflows that fall into the low to moderate range (by quantile rank) have increased, while high flows have not (Lins and Slack 1999). Li et al. (2010) emphasize the importance of atmospheric moisture flux convergence in determining the quantity P - E (precipitation minus evapotranspiration), which leads directly to streamflow.

Lenters (2004) showed trends of reduced seasonal cycle in net basin supply (NBS, which is tributary river inflow plus over-lake precipitation minus over-lake evaporation) and lake levels on Lake Superior. This change includes a reduction between 1948 and 1999 of the NBS during the spring, and an increase of NBS during the autumn. Each of these changes is primarily attributable to changes in runoff and over-lake precipitation, as given in the dataset of Croley and Hunter (1994). During the 1948-99 period, they did not note a strong overall trend in lake level.

A possible non-climatic cause of changes in the lake level regime of the Great Lakes was proposed by Baird and Associates (2005). They proposed that a deepening of the channel of the St. Clair River, which forms part of the connection between Lake Huron and Lake Erie, was responsible for a distinct reduction in the difference in level between these two lakes. IUGLS (2009) instead found that changes in climate during the period between about 1985 and 2005 was primarily responsible for this change in relative lake levels.

b. Frequency of localized, short-term extremes

As stated above, Pryor et al. (2009) showed an increase in the amount of precipitation that came on the 10 days of the year with the greatest precipitation. However, this was not evaluated as a proportion of the total precipitation. They also found that there was generally a decrease in the mean number of consecutive days without precipitation. This is in basic agreement with the results of the seminal paper of Kunkel et al. (1999).

Changnon (2007) examined the frequency, intensity, and economic impact of severe winter storms in the US between 1949 and 2003. This generally showed an increase in intensity over time, and a decrease in frequency, with these effects most concentrated in the eastern US.

c. Non-climatic influences

One factor aside from climate that can affect the long-term water budget of the region, as well as the shorter-term temporal characteristics of response of runoff to precipitation events, is land use. Andresen et al. (2009) showed that urban landscapes lower percolation of water into soil and increase surface runoff. Grassland landscapes have the lowest evapotranspiration (ET), while forests have the greatest amount of soil percolation. Cultivated agricultural land has fairly high ET, but also quite high surface runoff. They did not extend their analysis to include how much land was transformed from one of these classes to another. Mishra et al. (2010a) also evaluated the effects of land use on hydrology, showing that conversion of forest to cropland can lead to decreased ET and increased runoff. These effects, when combined with climate change effects, can be additive or compensating.

d. Lake water temperature

Austin and Colman (2007) investigated surface temperatures of Lake Superior during the period 1979-2006, and found a positive trend in these temperatures. They found the rate of increase in annual maximum lake surface temperatures to be nearly twice as large as trends in summertime near-surface air temperature over the surrounding land. This was taken as indicating positive feedback mechanisms within the lake, including greater intake of solar radiation due to the reduced duration and extent of ice cover, and the shift in timing of spring overturning of the water column.

Dobiesz and Lester (2009) investigated water temperatures , at the surface throughout the Great Lakes, and throughout the water column at one selected station in western Lake Ontario, and also associated water clarity. There was a strong trend toward greater water clarity (as measured by Secchi depth) between 1968 and 2002, which is attributable to a combination of abatement of phosphorus loads into the Great Lakes and the invasion of non-native Dreissenid mussels. They also found positive trends in water temperatures, both at the surface and at depth, and attributed this to a combination of changes in climate and changes in water clarity.

Some of the distinctions between the conclusions of Austin and Colman (2007) and Dobiesz and Lester (2009) illuminate a particular point. It has often been either explicitly or tacitly assumed that changes in temperature occur first in the atmosphere, and then propagate to changes in temperature of the surface (or other effects at the surface). Dobiesz and Lester (2009) hew close to this line of reasoning, implying that surface water temperatures are forced by surface air temperatures, with no notable effect in the opposite direction. Austin and Colman (2007), on the other hand, first present the difference in trends of water surface temperature and air temperature as being counterintuitive, but then offer mechanisms that occur within the water to explain this distinction. This means that the lake water is itself an active player in the climate system; we prefer to view climate and climate change as phenomena of the coupled atmosphere-surface system (including both land and water surfaces).

New datastreams (starting in 2008) for in situ measurement of fluxes of water vapor, trace gases, and sensible heat flux are documented in Blanken et al. (2011) and Spence et al. (2011). These researchers have initiated these measurements at one station each in Lake Superior and Lake Huron. These represent the first direct and ongoing measurements of evaporation on the Great Lakes, a dataset that will be valuable for analysis of the moisture and energy budgets of the lakes, and for calibration and validation of models.

3. Paleoclimatic studies

Booth et al. (2006) have characterized persistent anomalies in summer precipitation as being associated with anomalies in zonal surface winds. They show that July precipitation is negatively correlated with zonal wind index (mean sea level pressure gradient between 35º and 55º N across the western hemisphere), with a $p<0.05$ level of certainty for southern Minnesota, Iowa, and northern Missouri. Note that their zonal wind index gauges pressure gradients over a range of latitudes farther south than those indicated by the more widely-used North Atlantic Oscillation and Arctic Oscillation (NAO/AO) indices. Their examination of the possibility of explaining an extended drought in this region between about 1200 and 1400 CE is inconclusive.

Croley and Lewis (2006) examined climatic conditions under which some of the Great Lakes might have been terminal lakes in the past (i.e. lakes with no outflow point because they lose sufficient water to evaporation to offset precipitation and runoff inputs). They arrive at figures of water level as a function of changes in air temperature and precipitation relative to late 20th century climate (their Figures 7 and 8). These figures show a range of climates yielding lake levels above the sill, meaning that there is continuous outflow from the lake. They also show a range with seasonally and interannually intermittent outflow, with the water level always very near to the sill level. Then there is a range with water below the sill level; within this range, the mechanism of balancing the water budget through changes in outflow is removed, and the water level becomes highly sensitive to climate because the water budget must be balanced by changing the evaporation from the lake surface via changing the lake area as a result of changing the lake level until a dynamic equilibrium is reached.

4. Future projections

As in the historic record, model projections of precipitation rate generally show an increase of about 2% per degree C, while the water vapor content of the atmosphere increases by about 7%, implying longer residence time of water vapor in the atmosphere (Held and Soden 2006, Pan and Pryor 2009). Note also that, in order to maintain an equilibrium value of atmospheric water vapor content, surface ET integrated over the globe must equal precipitation integrated over the globe. Therefore, when integrated or averaged over the globe, the ET rate also increases by about 2% per degree C.

The magnitude of the most intense precipitation events has been projected to increase throughout the world due to increased greenhouse gases using both theoretical arguments (Trenberth et al. 2003) and analysis of output from global climate models (Sun et al. 2007). It is deemed likely that both floods and droughts will increase in frequency (Wetherald and Manabe 2002, Trenberth et al. 2003, Meehl et al. 2007). However, models remain a problematic tool for evaluating the magnitude and frequency of extremely heavy precipitation events, because in reality the spatial scale of the heaviest precipitation is smaller than the resolved scale of the model. This is true even for regional models with finer resolution than global models.

Some studies have projected a general increase in runoff for multiple drainage basins throughout the world (Wetherald and Manabe 2002, Manabe et al. 2004, Milly et al. 2005, Kundzewicz et al. 2007). Others have shown increases in the difference between precipitation and ET, which also imply increased outflow, and have extended these results to indicate increased soil moisture (Pan et al. 2004, Liang et al. 2006)

a. Upper Mississippi/Missouri/Hudson Bay watersheds

Using the Soil and Water Assessment Tool (SWAT), Lu et al. (2010) project that streamflow in the Upper Mississippi River basin will decrease when using climate data derived from GCM simulations in the 2046-65 period as compared to the 1961-2000 period. When averaging over the results using 10 different GCMs, these decreases occur during all seasons except winter. Wu et al. (2011) carried out similar projections for the Upper Mississippi River basin, and found increased water yield during the spring but large decreases in summer. The soil moisture likewise increases in spring and decreases in summer. Accordingly, there is increased risk of both flood and drought, depending on the season.

b. Ohio River watershed

Mishra et al. (2010b) used VIC driven by general circulation model output to investigate projected trends in drought in parts of Indiana and Illinois within the Ohio River watershed. They found that drought frequency increases during the middle part of the 21st century (2039-2068), while for later in the century, it increased only in the highest emission scenario for greenhouse gases.

c. Great Lakes watershed

Estimation of the impact of climate change on Great Lakes water budgets and levels began with Croley (1990). The same method has been used multiple times since then, but using results from different general circulation models (GCMs) as input (e.g. Lofgren et al. 2002, Angel and Kunkel 2010, Hayhoe et al. 2010). A recent and very comprehensive example of this approach, Angel and Kunkel (2010) assembled results from over 500 GCM runs from different modeling centers, using various greenhouse gas emission scenarios, and different ensemble members for each model configuration. They found spread among the results of the different model runs, but a general tendency for the lakes' net basin supply and water levels to be reduced, as was generally found in the preceding model studies using the same methods.

Lofgren et al. (2011), however, found fault with this long-used methodology, in particular its formulation of ET from land. This formulation relies excessively on using air temperature as a proxy for potential ET, and does not display fidelity to the surface energy budget of the GCMs that are used to drive the offline model of land hydrology. This is also in keeping with the findings of Milly and Dunne (2011). By substituting a simple scheme to drive the hydrologic model using changes in the GCMs' surface energy budget, rather than using the air temperature proxy as previously, Lofgren et al. (2011) projected water levels to drop by a lesser amount, or to actually rise in the future. The differential between water levels projected using the older method and the proposed new method differed by amounts on the order of one meter.

Cherkauer and Sinha (2010) used the Variable Infiltration Capacity (VIC) model to simulate changes in stream flow for six rivers. Although the title of the paper refers to the "Lake Michigan region," five of the six basins considered are in the Mississippi River system, located to the west or south of Lake Michigan. They found increased stream flow in these basins as a result of warming by anthropogenic greenhouse gases. The anticipated influence of variability, particularly in precipitation, is to both decrease low flows and increase peak flows.

Lorenz et al. (2009) evaluated the water budget for Wisconsin under climate change scenarios based on 15 atmosphere-ocean general circulation models (AOGCMs). They found that there was greater agreement among the various AOGCMs regarding the sensitivity of air temperature to increased greenhouse gases than in the changes in precipitation. They found a negative correlation during July and August between changes in air temperature and ET throughout the central United States, with maximum magnitude over the lower Mississippi River. This was taken to indicate that evaporative cooling was occurring, making both the surface and the lower atmosphere cooler when abundant ET occurred, and cloud formation associated with higher ET may also enhance this effect. They also found that the amount of precipitation that occurred in the single wettest day of the year increased by an average of 33%, although individual models had increases between 5% and 66%. These results are similar to those of Sun et al. (2007), mentioned above.

A newer wave of models will take a more direct approach at estimating hydrologic impacts of climate change in the Great Lakes basin. These involve development of regional climate models that are fully coupled to both the land surface and simplified formulations of the Great Lakes (Lofgren 2004, MacKay et al. 2009, Zhong et al. 2012, IUGLS 2012, M. Notaro and V. Bennington, personal communication). These Great Lakes-specific modeling efforts are complemented by downscaled climate models with a domain covering all of North America, created through the North American Regional Climate Change Assessment Program (NARCCAP, Mearns et al. 2009). Initial findings from these efforts (see, for example, Holman, et al, 2012) suggest a potential need to revisit historical climate and hydrological data sets for the Great Lakes region which, to date, have served as a basis for water budget and water level planning decisions including those impacting hydropower, navigation, and shoreline recreation and infrastructure.

d. Commonality among many studies

Throughout most of the projections based on general circulation models of future climate noted above, for the Midwest, there is an increase in the annual mean precipitation. And in most of them, increased precipitation happens primarily during the cold season. On the other hand, summer has little projected change or a decrease in precipitation in most models.

5. Coupled atmospheric-hydrologic phenomenon--Warming hole

Pan et al. (2009) show observational evidence of a summer "warming hole," a region in the contiguous United States in which warming trends are reduced or even reversed for the summer season. Depending on which period is used for calculation of trends, the warming hole is located over the western portion of the Midwestern region and extending further west and south (1976-2000), or primarily to the south of the Midwestern region (1951-75). The proposed mechanism is increased influx of moist air due to the low level jet (LLJ), originating from the Gulf of Mexico. The increased moisture content of the LLJ is a straightforward result of warming of both the atmosphere and the surface, particularly the water surface of the Gulf of Mexico. The resultant increase in rainfall leads to increased evaporative cooling of the surface (note that the cooling effect is most pronounced for daily maximum temperatures during the summer). As noted, the location of the warming hole has shifted with time, and the mechanisms behind this shift are unclear.

6. Uncertainty and Probability

Acknowledging and quantifying uncertainty in historical climate data and climate projections, and clearly propagating that uncertainty into policy and management decisions, represent an ongoing challenge to the water resource and climate science community and the general public. Misconceptions about uncertainty, and the confusion associated with knowledge versus ignorance (Curry and Webster, 2011), have important implications for the water resource-climate science nexus, and (following Van de Sluijs, 2005) have led to the term "climate monster", a term intended to reflect that confusion, and represent a source of fear that drives reactions to a future we do not understand and can not control (Curry and Webster, 2011). Confirming and validating models is, of course, one approach to potentially building confidence in projections about future climate conditions, however there is no clear consensus within the water resources or the climate science community about a metric, or set of metrics, for which the skill of complex (and in some cases, probabilistic) models can be assessed (Guillemot, 2010).

Furthermore, agreement between a model and historical climatic data does not necessarily imply that projections of future climate states will be correct, or even physically reasonable, especially if the model is based more on empirical fitting rather than processes known from first principles. Curry and Webster (2011) say, "Continual ad hoc adjustment of the model (calibration) provides a means for the model to avoid being falsified." A particular example of the problem with empirically-based models being applied to unprecedented climate regimes is illuminated in Lofgren et al. (2011), in this case leading to demonstrably excessive sensitivity of ET to climate.

Precipitation and ET are variables for which the uncertainty of their sensitivity in the context of climate change is greater than the uncertainty of air temperature, as emphasized by Pan and Pryor (2009) and Lorenz et al. (2009). To compound this issue, the most important quantity in determining streamflow and lake levels is the difference between precipitation and ET. Thus it is the difference between two larger quantities, each having sizable uncertainty, and therefore the uncertainty proportional to this difference is even larger.

Additional insights into management of water resources in the face of uncertainty, as well as reviews of many of the findings mentioned in the current paper, can be found in Brekke et al. (2009).

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